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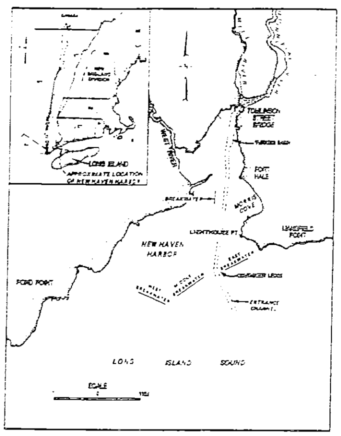

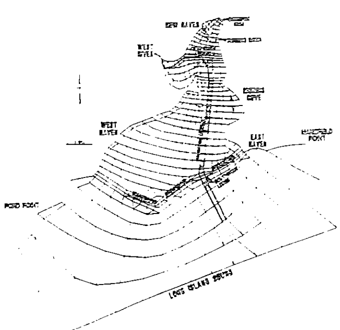

HYDRAULICS LABORATORY

TECHNICAL REPORT HL-88-24

NEW HAVEN HARBOR NUMERICAL MODEL STUDY

by

David R. Richards

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

September 1988
Final Report

Approved For Public Release; Distribution Unlimited

Prepared for US Army Engineer Division, New England
Waltham, Massachusetts 02254-9149

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report HL-88-24	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Hydraulics Laboratory 6b. OFFICE SYMBOL *(If applicable)* CEWES-HE-E	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS *(City, State, and ZIP Code)* PO Box 631 Vicksburg, MS 39181-0631	7b. ADDRESS *(City, State, and ZIP Code)*
8a. NAME OF FUNDING/SPONSORING ORGANIZATION USAED, New England 8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS *(City, State, and ZIP Code)* 424 Trapelo Road Waltham, MA 02254-9149	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
New Haven Harbor Numerical Model Study

12. PERSONAL AUTHOR(S)
Richards, David R.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Final report	FROM ____ TO ____	September 1988	76

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield VA 22161.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

Currents	Long Island Sound	Numerical modeling
Estuaries	New Haven Harbor	Tides

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report presents the results from a numerical model study of the impacts of deepening and widening the approach channels and inner turning basin in New Haven Harbor, CT. Results from the study were intended to determine changes in circulation, which might affect valuable oyster resources, and to form the current fields needed to provide a detailed ship simulation study of the navigation improvement project. The US Army Corps of Engineers numerical modeling system, TABS-2, was used to predict the changes that might occur to circulation patterns in New Haven Harbor and portions of Long Island Sound. Currents were predicted in the navigation channel as well as in distant shallow regions where there is a significant shellfish fishery. Results from the numerical model study indicated that there were perceptible changes in the circulation patterns but that the magnitude of the changes was very small. In most cases, base-minus-plan differences in the

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)*	22c. OFFICE SYMBOL

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

19. ABSTRACT (Continued).

currents were less than 0.1 fps. The largest differences occurred in the deepened channels, away from the shallow oyster bed areas. No tide differences were detected between base and plan.

PREFACE

In May of 1987, the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, was requested by the US Army Engineer Division, New England (CENED), to conduct an investigation of possible tidal circulation changes in the New Haven Harbor area caused by the proposed deepening and widening of the navigation channels and turning basins. Results from the study were intended to provide current fields for later ship simulation studies.

The study was funded by CENED and conducted by HL personnel under the general direction of Messrs. F. A. Herrmann, Jr., Chief, HL; R. A. Sager, Assistant Chief, HL; W. H. McAnally, Chief, Estuaries Division (ED); and W. D. Martin, Chief, Estuarine Engineering Branch (EEB). The project was conducted and this report prepared by Mr. D. R. Richards, EEB. Mr. Mark Bardwell, ED, assisted in the construction of the numerical model mesh. This report was edited by Mrs. Marsha C. Gay, Information Technology Laboratory, WES.

COL Dwayne G. Lee, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
miles (US nautical)	1.852	kilometres
miles (US statute)	1.609344	kilometres
pounds (force)-second per square foot	47.88026	pascal-seconds

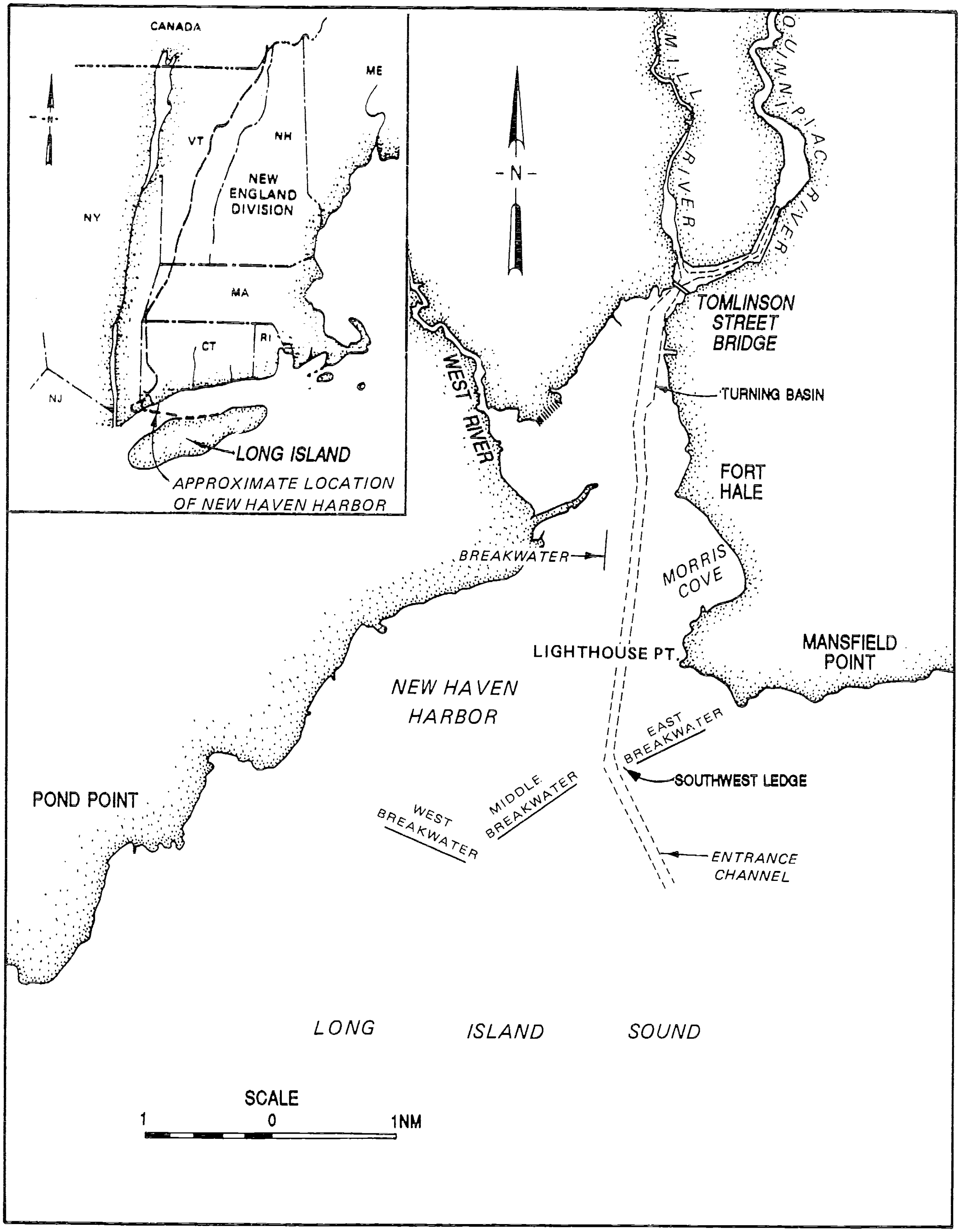

Figure 1. Vicinity and location map

NEW HAVEN HARBOR NUMERICAL MODEL STUDY

PART I: INTRODUCTION

Background

1. New Haven Harbor (Figure 1) is the largest port in Connecticut and the second largest in New England, based on commercial tonnage. Only the port of Boston is larger in the New England area. Over 90 percent of the tonnage is in the form of petroleum products with the remainder consisting of such varied products as chemicals, metal scrap, lumber, minerals, and automobiles.*

2. The vessels that transport these commodities to and from the harbor have experienced navigation difficulties due primarily to the limitation imposed by the existing 35-ft** channel depth. This depth often limits the use of the harbor to within just a few hours of high tide or, in the case of the larger vessels, requires off-loading in the deeper Long Island Sound. Other navigation difficulties include channel alignment problems, which are most noticeable between the breakwaters during storm conditions, and the congestion in the turning basin when vessels are transiting near the time of high tide.

3. The New Haven Harbor Navigation Improvements project was authorized for construction by the Water Resources Development Act (WRDA) of 1986. In its authorization, the WRDA required that the US Army Corps of Engineers investigate the impact of project construction, operation, and maintenance on the oyster resource within New Haven Harbor. New Haven Harbor is the most intensively farmed shellfish area in New England with a significant portion of the harbor being leased from the State of Connecticut for commercial operations. Oyster seed stock is the primary farmed product but quahogs are also produced. Due to pollution, recreational shellfishing is prohibited, and commercially farmed shellfish must be removed from the harbor for transplantation or depuration. Environmental interests require that the proposed channel

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* US Army Engineer Division, New England. 1981 (Apr). "New Haven Harbor, Connecticut, Feasibility Report; Coastal Development for Navigation," Waltham, MA.

** A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

improvements not place the harbor in a more environmentally hazardous condition.

4. With this requirement in mind, the US Army Engineer Division, New England, asked the US Army Engineer Waterways Experiment Station (WES) to conduct a numerical model study of the effects of proposed channel modifications on the existing circulation patterns in the harbor. The requested study was designed to provide hydrodynamic results that would be useful in future ship simulation and environmental studies.

Project Description

5. The proposed channel improvements were designed by the New England Division to accommodate vessels that were projected to use the harbor in the future. The design included deepening the channel over a distance of approximately 6.9 miles from 35 ft to 40 ft below mean low water,* widening the approach channel over a distance of approximately 4 miles from 400 to 500 ft, widening the channel bend at Southwest Ledge from 560 to 780 ft, and providing a common turning basin shaped as an irregular octagon, approximately 1,200 ft wide and 40 ft deep at the head of navigation (Figure 1).

Purpose

6. The purposes of the numerical model study were to describe numerically the existing hydrodynamics of the harbor and to determine the departure from this condition caused by the proposed channel improvements. Hydrodynamic results from the model would then be provided to others for ship simulation and environmental studies.

Approach

7. A finite-element mesh that covered all of New Haven Harbor and a significant portion of Long Island Sound was constructed to include all of the navigation channels as well as the extensively farmed shellfish beds in

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* All elevations (el) cited in this report are in feet referred to mean low water (mlw).

shallow waters. The designed mesh was sufficiently refined to allow the observation of circulation patterns that might depart from existing conditions throughout the harbor. Once the existing (base) conditions were determined, the plan channel depths and widths were incorporated into the numerical model and plan conditions determined. Spring tide conditions were determined to be the most important for the study. Since freshwater flows comprise a very small portion of the total flow entering and exiting the harbor, they were eliminated as a pertinent boundary condition in this study.

PART II: DESCRIPTION OF THE MODEL

TABS-2

8. TABS-2 is the name of a family of computer programs used in the two-dimensional modeling of hydrodynamics, sedimentation, and constituent transport in rivers, reservoirs, bays, and estuaries. The system was developed by the Hydraulics Laboratory at WES* from the finite-element, hydrodynamic, and sediment transport models originally developed by Resource Management Associates, Inc., in Davis, CA. Significant enhancements to the codes have allowed for applications to a wide class of computational hydraulics problems. The system contains all of the necessary preprocessing and post-processing utilities needed to allow relatively user-friendly applications.

RMA-2V

9. The hydrodynamic model, RMA-2V, solves the depth-integrated equations for conservation of mass and momentum in two horizontal directions. The finite-element method, using Galerkin weighted residuals, is employed to solve the conservation of mass and momentum equations. Bottom friction is calculated using the Manning's equation, and eddy viscosity coefficients are used to estimate the effects of turbulence.

10. The finite-element mesh may contain quadrilaterals, triangles, or a mixture of the two; and each element may have parabolic sides. Elemental shape functions are quadratic for flow and linear for depth. Integration in space is Gaussian. Derivatives in time are replaced by nonlinear finite difference approximations.

11. The finite-element solution is fully implicit, and the set of simultaneous equations is solved by Newton-Raphson iteration. The solution is achieved using a front-type matrix inversion that assembles a portion of the matrix and solves that portion before assembling the next portion of the matrix. A description of the model is given by Thomas and McAnally.*

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* W. A. Thomas and W. H. McAnally, Jr. 1985 (Jul). "User's Manual for the Generalized Computer Program System: Open-Channel Flow and Sedimentation, TABS-2; Main Text and Appendices A through O," Instruction Report HL-85-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

PART III: MODELING PROCEDURES

Mesh Design

12. The numerical model mesh was designed to allow accurate replication of the tidal circulation throughout New Haven Harbor north of the breakwaters and a significant portion of Long Island Sound (Figure 2). The mesh was sufficiently refined to allow a solution of the distinct lateral gradients that were suspected in and around the navigation channel and the breakwaters where there were substantial changes in geometry. A high level of resolution was included in the more uniform shallow depths of the harbor as well because of

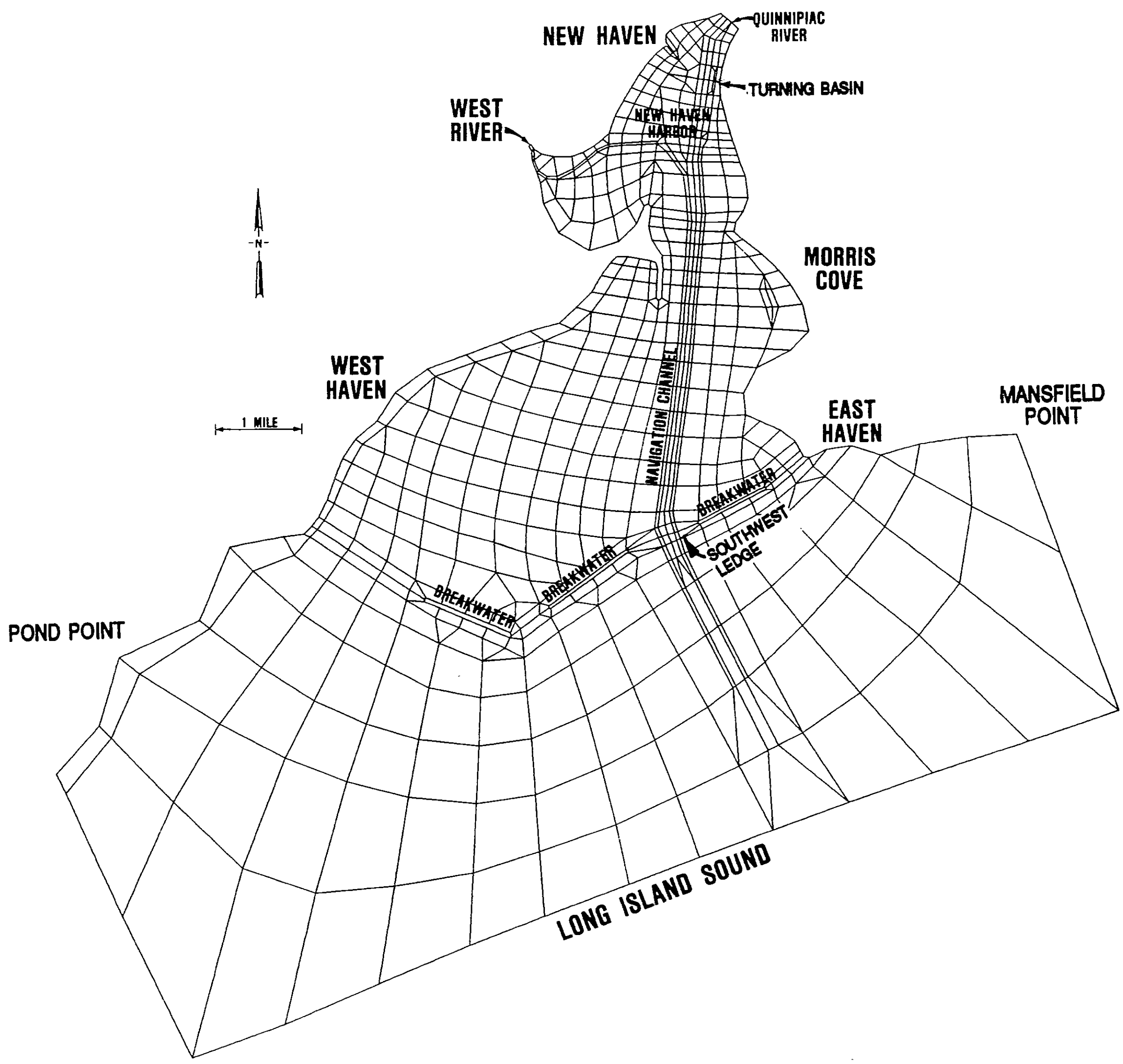

Figure 2. New Haven Harbor numerical model mesh

the interest in the impact on shellfish. In either case, there was enough resolution to adequately define the impacts of the proposed project at discrete intervals no farther than 500 ft apart throughout the harbor north of the breakwaters. The confined channel areas between the breakwaters and the northern harbor were typically represented in much greater detail.

13. Model geometry for the base condition was defined by the National Oceanic and Atmospheric Administration (NOAA) Chart 12371 dated 1985. Additional bathymetry was provided by the New England Division in areas of poor coverage, particularly in the turning basins and Morris Cove. The plan condition was constructed by moving nodes to define channel realignments and increasing the water depths at nodes where deepening was planned.

14. A total of three meshes were developed over the course of this study. The first used a curved Long Island Sound boundary that extended from Pond Point on the west along an arc to Mansfield Point on the east. Since the tide was nearly in phase along this arc, the original idea was to have the downstream boundary condition a common elevation varying through time. Since the ebb and flood currents in Long Island Sound were primarily of importance to ship simulations alone, the collected prototype data would be sufficient in the lower navigation channel without modeling.

15. Early in the study it was determined that the Long Island Sound current caused some unusual current patterns on the north side of the breakwaters as well. While flood currents north of the breakwaters normally headed into the harbor, near the western breakwater the flood currents appeared to head out of the harbor. It became necessary to develop the second mesh that duplicated the Long Island Sound current (Figure 2). This was accomplished by moving nodal points in Long Island Sound and specifying boundary conditions with a combination of water elevations and current velocities.

16. A third grid was developed from the second by adding elements to the upper rivers. This allowed studies to be conducted north of the Tomlinson Street Bridge on the Quinnipiac River and farther upstream on the West River. This mesh was developed to allow salinity intrusion studies if they were requested and to allow more flexibility in the specification of upstream boundary conditions should alternative tide or freshwater flow conditions be needed. At the time of this reporting, there were no plans to conduct these types of studies. The studies conducted and described in this report were based entirely on the second mesh.

Boundary Conditions

17. Boundary conditions for the study were obtained from a field survey conducted by WES and the New England Division on 16 June 1987. This was a period of spring tides as requested by the New England Division. Tide and velocity data were collected for the purposes of providing boundary conditions for the simulations as well as a verification data set. Suspended sediment, bottom sediment, and salinity samples were also collected in case sediment transport or salinity studies would be required at a later date. A detailed report on the field survey is given in Dozier.*

18. The numerical model mesh used for the study required velocity or water-surface elevation boundary conditions to be used at all model boundaries except for the slip-flow conditions used on the shorelines and breakwaters. On the rivers, depth-averaged velocities from the field data were used to simulate the excursion of the tide and flow into and out of the modeled region. Laterally along these boundaries, a parabolic shape was imposed on the incoming and outgoing velocities to mimic the natural effects of friction in the shallow areas near the banks. The riverine boundary conditions are shown in Figure 3.

19. The need to simulate Long Island Sound currents required an unusual treatment of the Long Island Sound boundary. The nearly straight row of nodes in the southernmost portion of the mesh (Figure 2) was located far enough away from the entrance of New Haven Harbor not to experience a velocity component normal to the boundary, but rather be aligned with the predominant direction of the ebb and flood currents in the sound. This alignment allowed this portion of the grid to be specified as a slip boundary with no forced elevation or velocity.

20. The western portion of the Long Island Sound boundary was specified as a water-surface elevation boundary since a tide gate with reliable data was located on this line. The eastern portion of the Long Island Sound boundary was also located on a tide station, but the differences in tidal amplitude, phase, and offset were indistinguishable from those collected on the western end. However, a nearby velocity station at the beginning of the navigation

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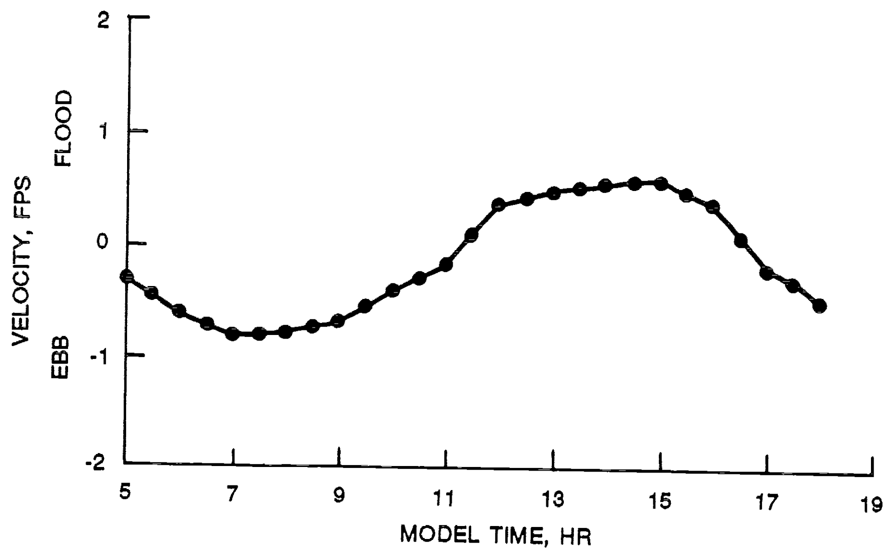
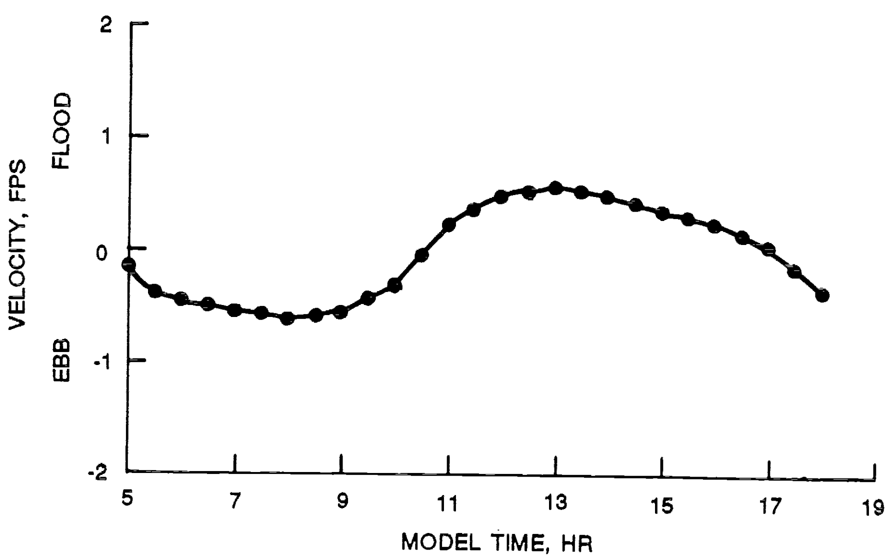
* T. S. Dozier. 1988 (Sep). "Field Investigation of New Haven Harbor, Connecticut," Miscellaneous Paper HL-88-8, US Army Engineer Waterways Experiment Station, Vicksburg, MS.



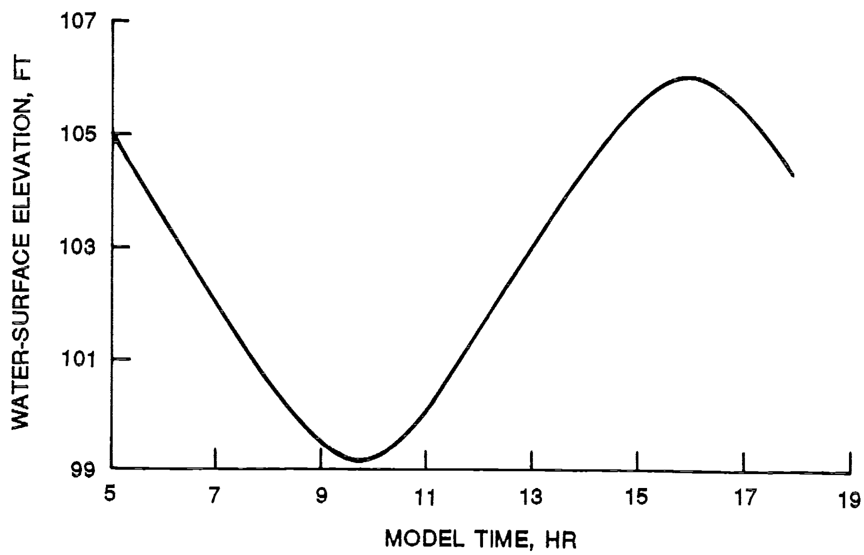
a. Quinnipiac River



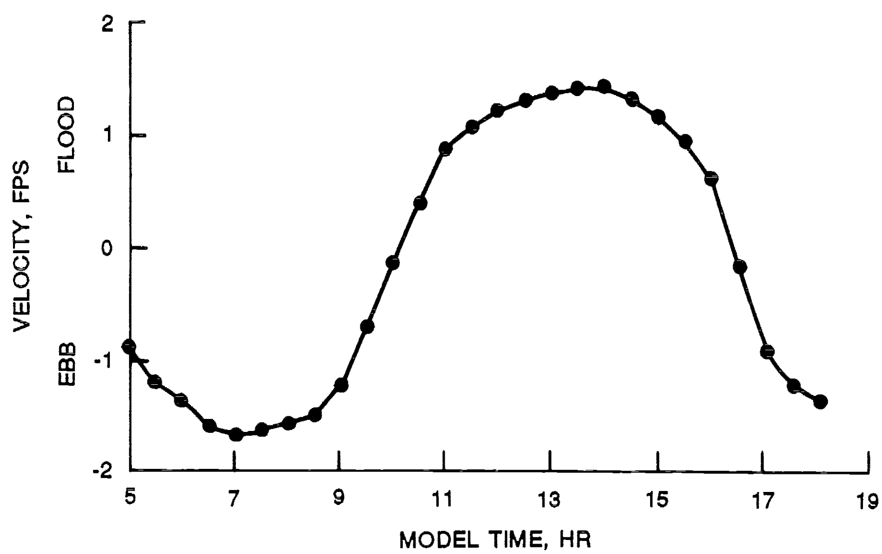
b. West River

Figure 3. Riverine boundary conditions

channel provided some reliable velocity data to drive this boundary. Velocities from this station were amplified slightly and applied to the eastern boundary. The amplification allowed the model to reproduce field conditions. The tide and velocity boundary conditions for Long Island Sound are given in Figure 4.



a. Tide



b. Velocity

Figure 4. Long Island Sound boundary conditions

PART IV: MODEL VERIFICATION

Field Data

21. The verification data set came from 19 field stations located throughout New Haven Harbor and Long Island Sound (Figure 5). Velocity, salinity, and suspended sediment measurements were taken at surface, middepth, and bottom at each overboard sampling station. Verification tide stations were located at Fort Hale on the eastern bank of New Haven Harbor and farther upstream at the Tomlinson Street Bridge on the Quinnipiac River.

22. The field data indicate that there is very little salinity stratification anywhere in the project area. In general, there are negligible variations in space or time. Long Island Sound, during the sampling period, provided a stable, uniform source salinity to the harbor, which when combined with negligible freshwater inflows from the rivers provided the functionally homogeneous salinity conditions. This homogeneity apparently occurs most of the time in the harbor, so the sampling period was not anomalous.

23. An inspection of the field velocities revealed some unusual characteristics in the harbor. New Haven Harbor with its irregular shape, three breakwaters, inner sandspit, numerous dock slips, and substantial power plant and sewage treatment flows, provides a highly turbulent environment. The significant tide range and the oblique attack of the tides and currents from Long Island Sound add to the turbulence and result in significant eddies and unusual flow circulations that vary significantly through time. The breakwaters at the entrance cause the formation of large eddies whose size and orientation depend on the timing and strength of tides and currents from Long Island Sound. Smaller eddies and short-period wave reflections occur as well, most noticeably in the upper harbor due to the irregular pier slips and near-vertical sidewalls at the shoreline.

24. These processes are highly dynamic and their individual effects would be nearly impossible to identify given the discrete nature of the field data collection exercises. Signals with periods less than 1 hr are not easily picked up given the scope of this study; therefore, there is ample reason for the field velocities to contain considerable noise. The data set does, however, provide sufficiently detailed information to allow a meaningful verification.

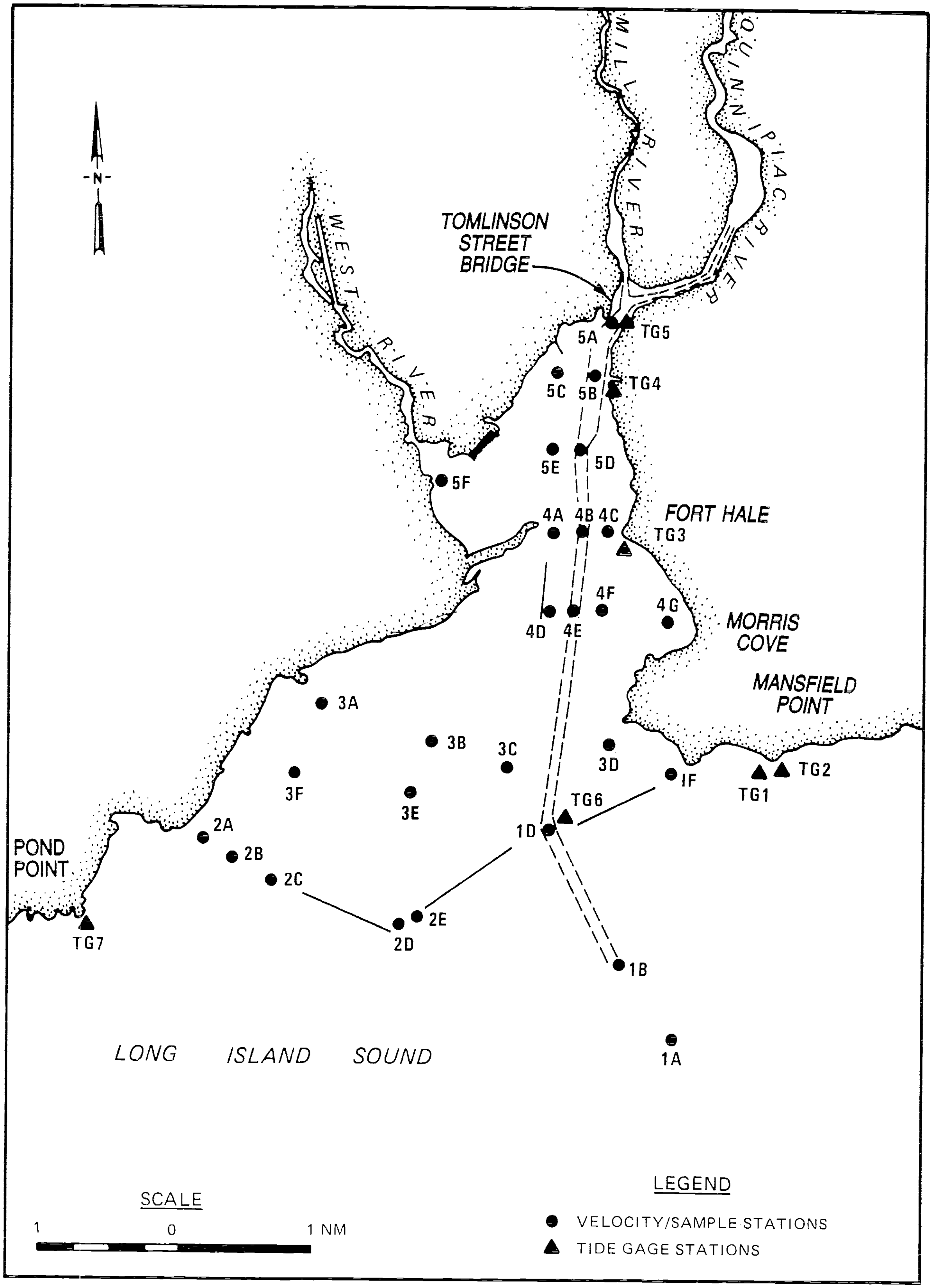


Figure 5. Verification data stations

25. First, the salinity and velocity field data determined that a two-dimensional, vertically averaged model would provide a reasonable tool to evaluate base and plan conditions. This might not have been true if the water column were highly stratified. Second, the data collection exercise covered areas outside the navigation channels, which is often not the case in larger studies or those with limited resources. In this way, the impacts on shellfish were given as much emphasis as the effects on navigation.

Model Verification Procedure

26. Very little model adjustment is required to verify numerical models if the governing equations describe the problem, sufficient resolution is used, and the boundary conditions are accurate and meaningful. Indeed, if the mesh is properly constructed and reasonable boundary conditions used, the remaining adjustment of coefficients should provide only minor variations in the output, given that they were based on real-world phenomena and not numerical expediency

27. In RMA-2V, only two coefficients can be adjusted in the verification process: elemental Manning's n for roughness and eddy viscosity for turbulence characteristics. Both the scientific literature and a significant amount of experience in verifying numerical models suggest that a case can be made for assigning global Manning's n values based not only on the type of water body modeled and the flow conditions, but also as a function of depth within the model. The values used in this model study are given in the following tabulation:

Element Depth, ft	Manning's n
0-8	0.022
9-16	0.021
17-24	0.020
25-32	0.019
33-40	0.018
41+	0.017

These were the initial values used, although sensitivity analyses with other values were performed. Changes in the values yielded slightly different results, but none provided a better verification.

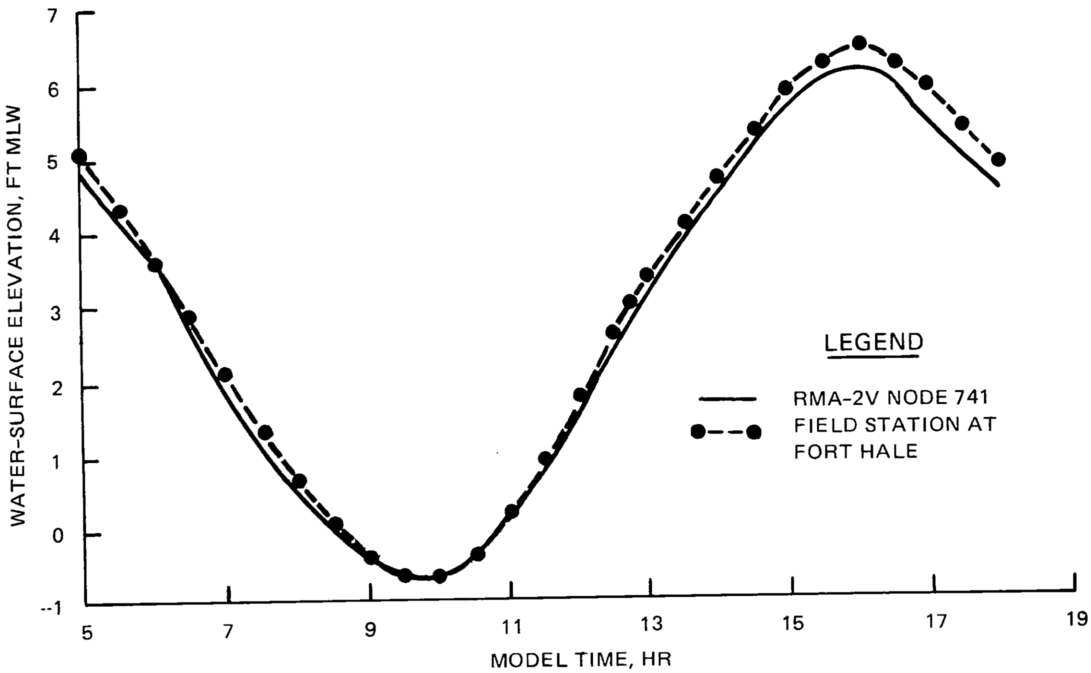
28. Eddy viscosity coefficients are the only other adjustment

coefficients used in RMA-2V. In theory, they are designed to account for turbulence that is indeed present in the prototype but cannot be modeled unless a more rigorous and significantly more expensive turbulence closure model is used. A common manifestation of using values that are too large is the smearing of velocities to the point of lateral uniformity when lateral gradients in the velocity fields are expected.

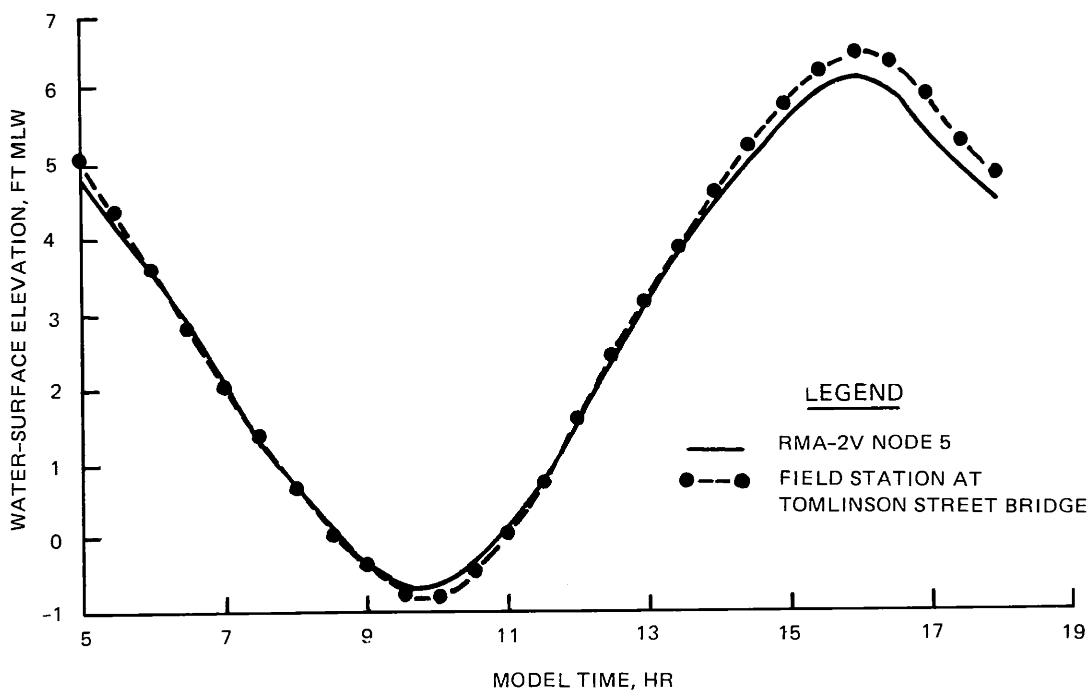
29. A significant amount of experience in both numerical and physical flumes as well as prototype scale problems indicates that, in general, the lower the eddy viscosity value, the better the results. In prototype scale problems of estuaries, it is rare to have stable model results with eddy viscosity coefficients that are too small. For economic reasons most grids are sufficiently coarse to require a certain amount of viscosity to maintain model stability. In most cases, this minimum amount of viscosity for stability is close to that required based on the physics of the problem. All models used today in computational hydraulics contain some amount of viscosity, whether it is supplied manually to the simulation or it is intrinsic to the solution technique. It is not an alarming consideration provided that reasonable numbers are used. In this study, the eddy viscosity used in the xx-, xy-, yx-, and yy-directions was 50 lb-sec/ft^2. Simulations were conducted using values as low as 20 lb-sec/ft^2, but stability was more difficult to obtain with no improvement in the results.

Tide Verification Results

30. Evidence that reasonable verification procedures were used is shown in the model results. Figure 6 gives a comparison of model versus prototype measurements for the Fort Hale tide station near the middle of the harbor and the Tomlinson Street Bridge tide station at the northernmost end of the harbor on the Quinnipiac River. Agreement between model and prototype is quite good at both stations in the harbor. The entire harbor is nearly in phase in both model and prototype. Slight differences in the tide elevations near high water can be explained by the source tide being slightly different from the actual tides measured in the field. In the interest of constructing a repeatable source tide for use in more lengthy simulations, a smoothed tide was used on Long Island Sound. This is entirely responsible for the slight differences between model and prototype.



a. Fort Hale



b. Tomlinson Street Bridge

Figure 6. Tide verification results

Velocity Verification Results

31. Velocity verification was achieved despite a significant amount of noise in the prototype data. In this case, noise consisted of short-period oscillations in the harbor such as seiching, wind wave and longer wave reflections off vertical shorelines and breakwaters, variations in velocity magnitude and directions due to eddy shedding, instrument error, and operator error. Many of the velocity field measurements were taken near the threshold limits of the instruments. Turbulence was noticed in the field measurements in the form of fluctuations in magnitude and direction over the several seconds when measurements were taken at each depth. Depending on the exact instant when the measurements were taken, there could be as much as a 10- to 50-percent change in magnitude and a 0- to 90-deg change in direction.

32. An additional complication was that the sampling boats were tied to buoys or anchors during the sampling so there was a considerable swing in position depending on the time in the tide cycle. This could easily amount to a change in horizontal position of between 100 and 200 ft depending on the depth of the water and length of anchor line. For stations located near abrupt geometry changes such as breakwaters or channel drop-offs, position changes of this magnitude could place the boat inside or outside a large eddy. This is particularly true near the breakwaters. A different method of anchoring could have minimized the amount of swing but would have resulted in a less dense sampling coverage. It should be noted that no correction has been made in the velocity comparisons for changes in the position of the boat.

33. Figure 7 compares depth-averaged velocities for the model and prototype for 15 stations located throughout New Haven Harbor. Station designations are shown in Figure 5. For the most part, comparisons are good considering that no corrections were applied for changes in vessel position. Peak ebb and flood velocities in the model agree with the prototype in most cases even though the shape of the time-history differs. The smooth shape of the prototype velocity time-history in the Long Island Sound stations further illustrates the point that the area north of the breakwaters contains considerably more turbulence than Long Island Sound. Model to prototype velocity agreement in the sound is excellent.

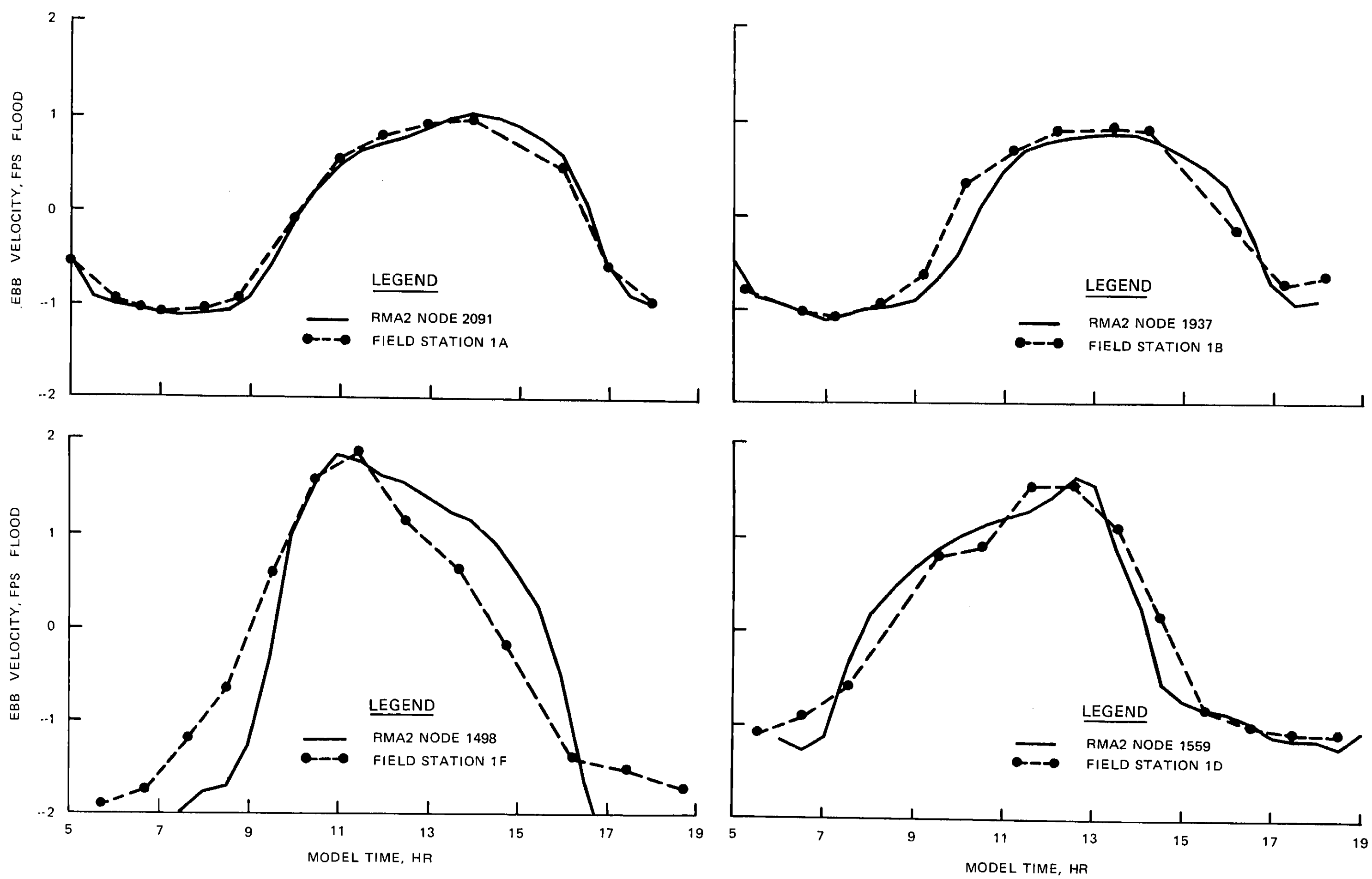
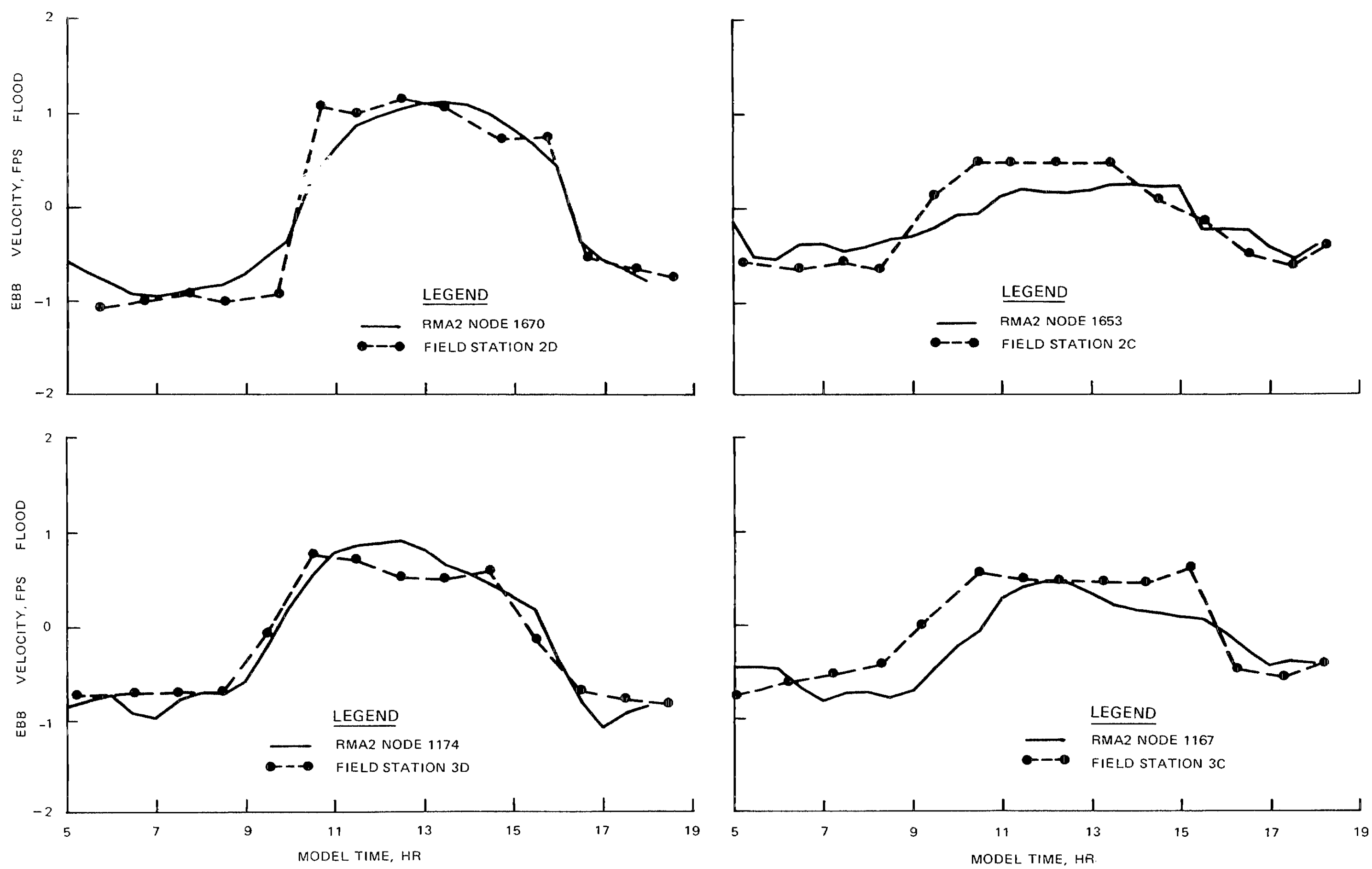


Figure 7. Velocity verification results (Sheet 1 of 4)



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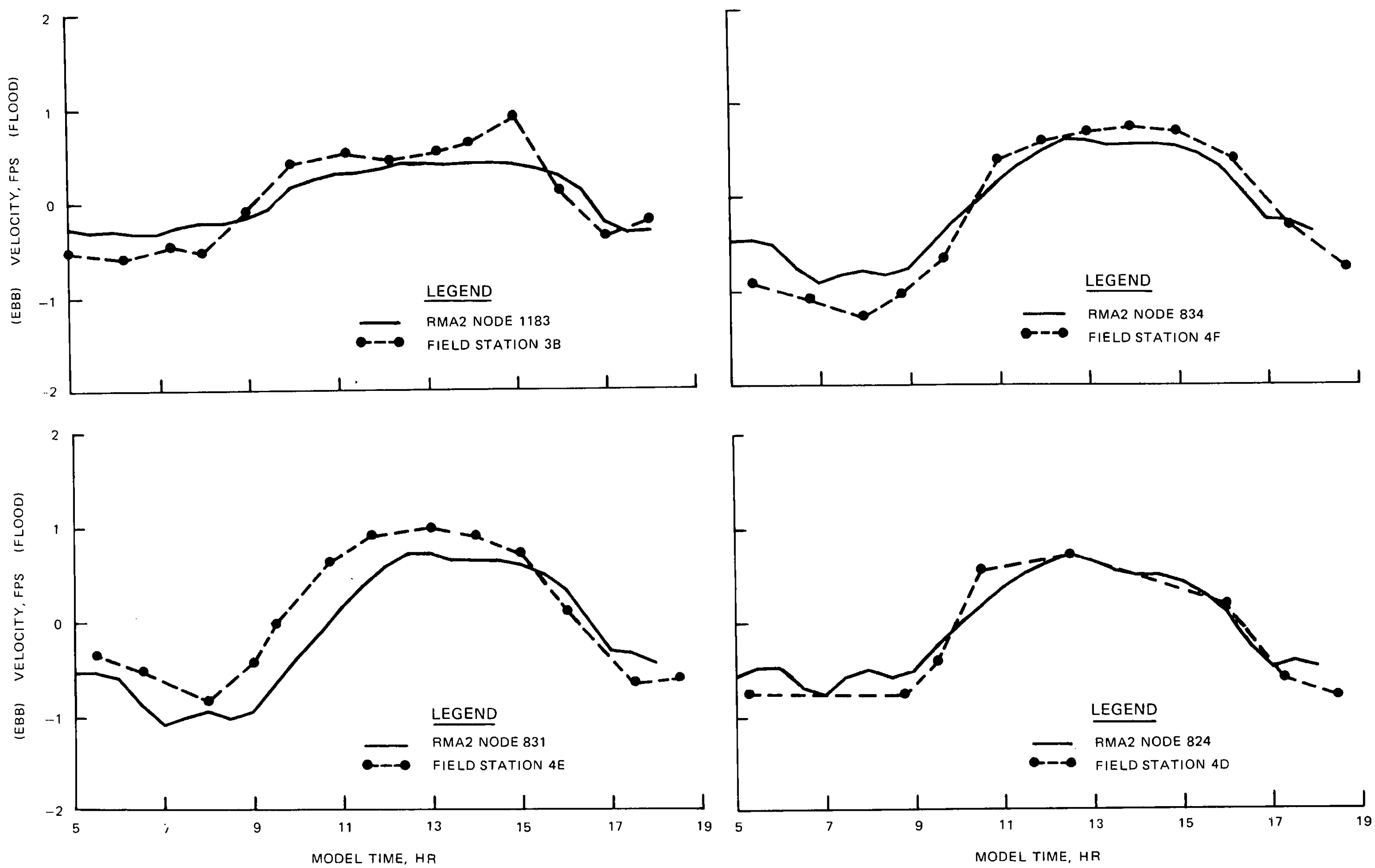

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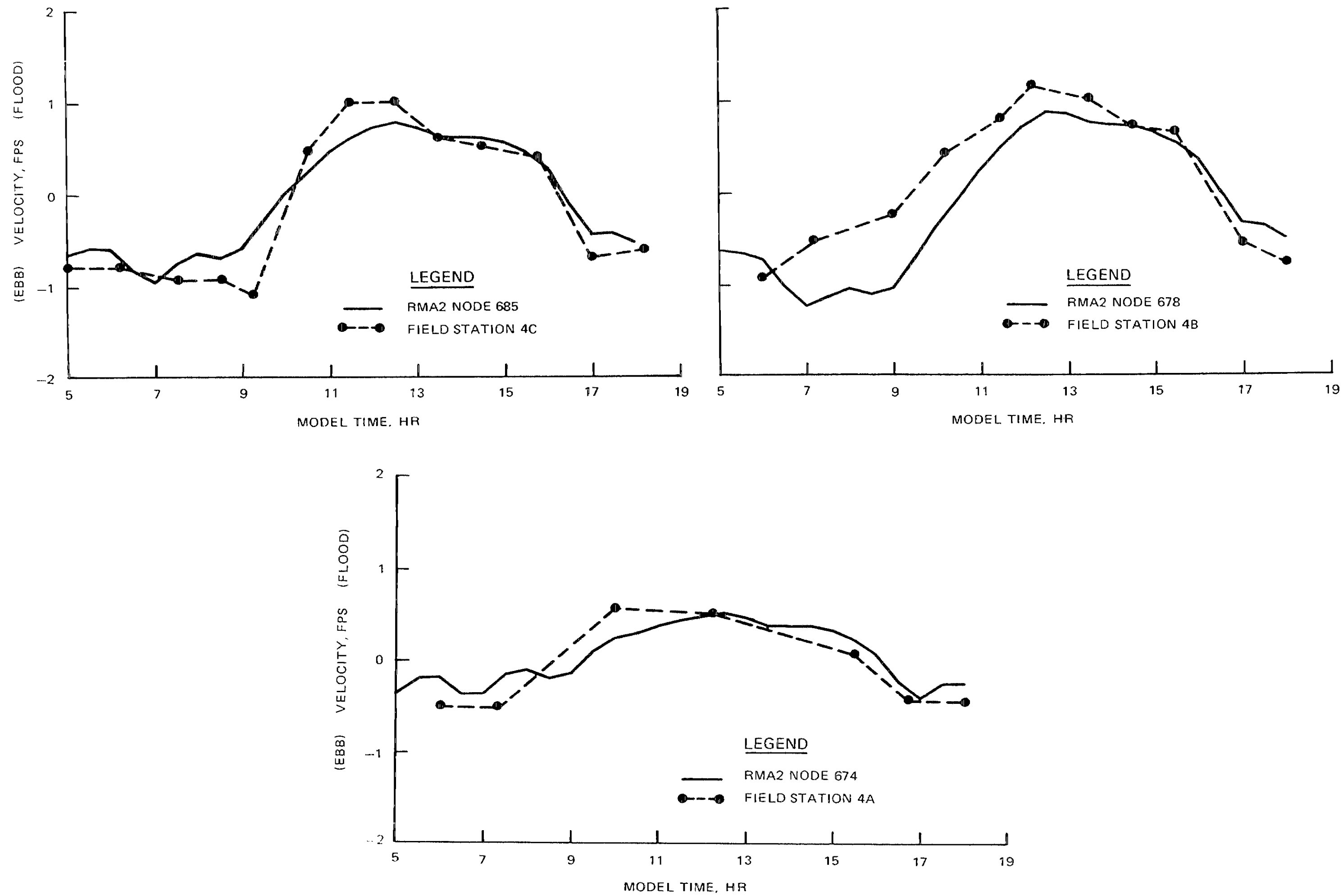


Figure 7. (Sheet 4 of 4)

PART V: MODEL RESULTS

Tide Results

34. An examination of the tidal results from the numerical models indicated that there was virtually no difference in phase, amplitude, and plane between the base and plan conditions. This was somewhat predictable since the harbor tide is dominated by the conditions in Long Island Sound with very little tidal phase or amplitude change within the harbor.

Velocity Results

35. Before the differences between the base and plan velocities are presented, it is useful to discuss the existing circulation in the harbor as described by the numerical model. A good understanding of the existing circulation patterns is essential to assess impacts caused by the plan condition.

36. During the initial investigation a considerable amount of effort was expended to gather all of the available data and knowledge concerning New Haven Harbor. This investigation began by gathering tide tables and other published information as well as meeting with local people. The meetings with local people, particularly the pilots and fishermen, provided valuable information that was later used to judge the accuracy of the modeling.

37. Discussions with the pilots provided information on the strength of the Long Island Sound currents, changes in the direction and magnitude of those currents as ships pass through the breakwaters, and the subtle changes in the currents as the ships head into the harbor. Currents felt by the pilots varied as a function of time in the tide cycle and other external forces such as wind strength.

38. Fishermen provided information that suggested certain conditions inside the breakwaters resulted in the oyster beds being physically disturbed or scoured. There was no consensus as to what conditions caused the scouring of the beds, but most thought it was associated with a particular tide condition. The scouring was most noticeable behind the middle breakwater near the navigation channel.

39. The numerical model provided results in the base condition that seem to corroborate the opinions of the pilots and fishermen. Figures 8 and 9

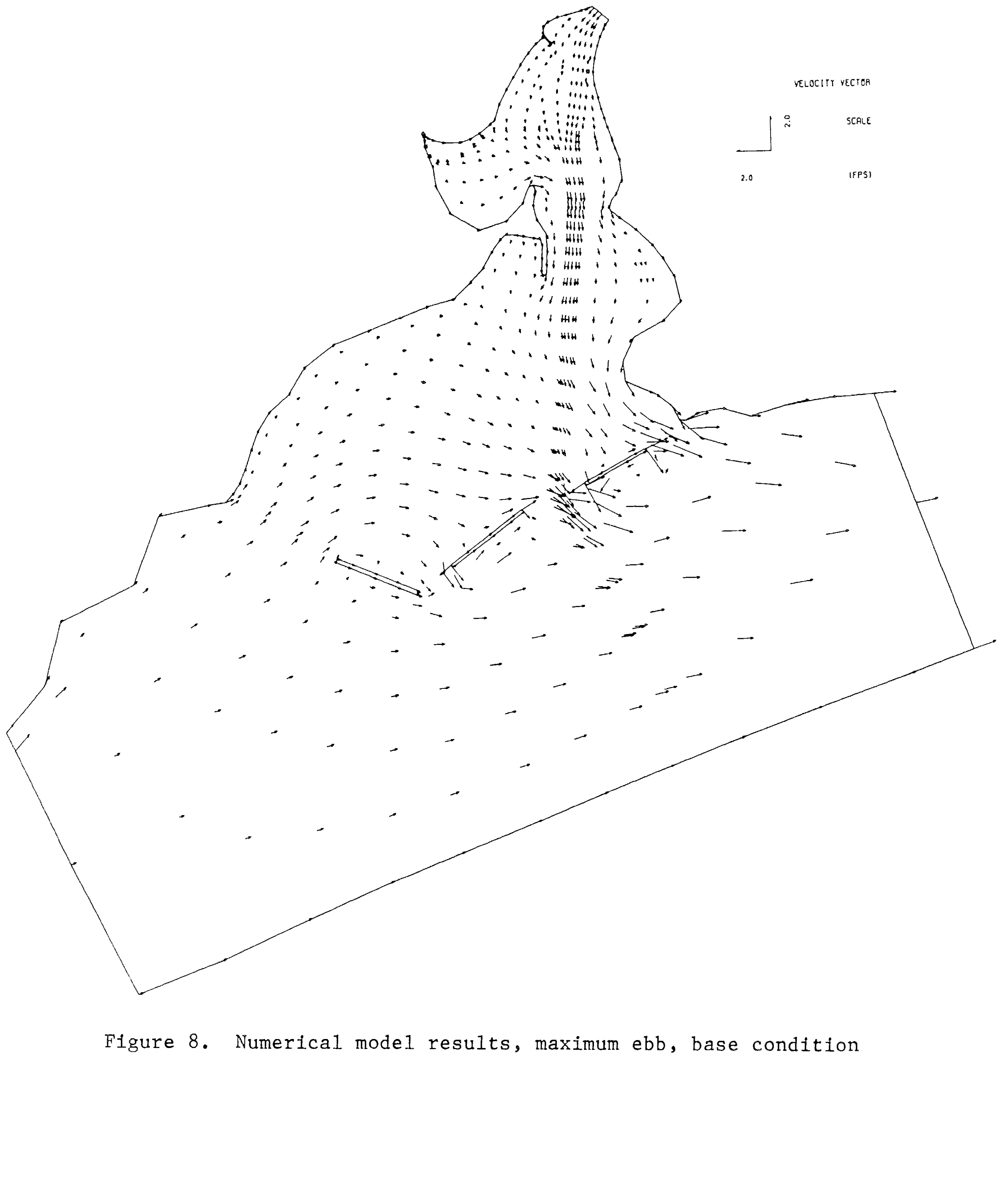


Figure 8. Numerical model results, maximum ebb, base condition

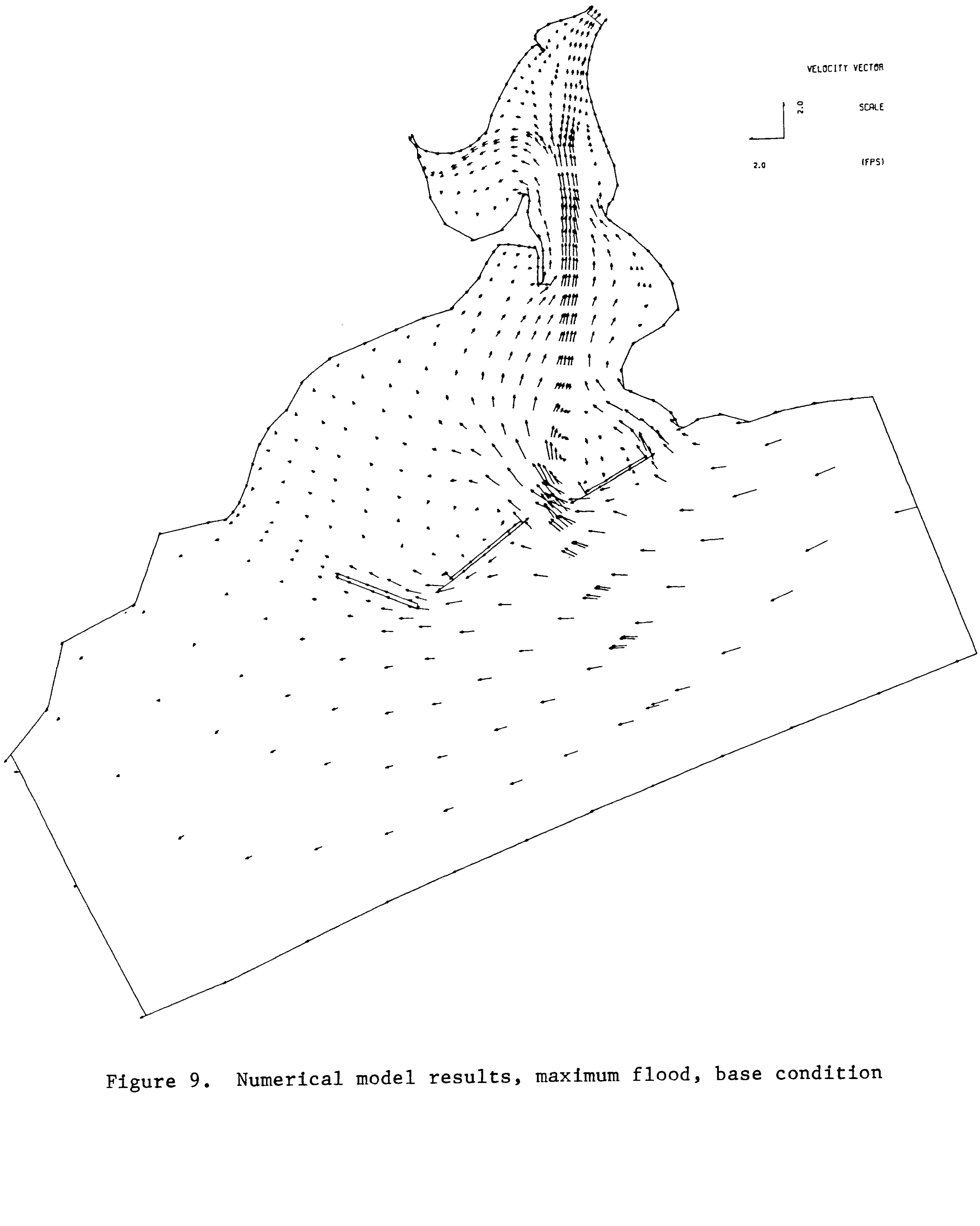


Figure 9. Numerical model results, maximum flood, base condition

provide model velocities for maximum ebb and flood, respectively, for the base condition.

40. A substantial Long Island Sound current is produced that flows parallel to the breakwaters during maximum ebb and flood flows. Currents through the openings in the breakwaters show a significant increase in speed and change in direction. There is a substantial gradient in velocity field across the opening in the breakwaters that is reversed between flood and ebb. Once the flows pass through the opening, they leave the navigation channel and proceed over the more shallow areas that contain the oyster beds. Large eddies are produced behind each breakwater that move throughout the tidal cycle.

41. The existing oyster bed scouring noted by fishermen could easily be caused by strong spring tides from Long Island Sound or wind-driven surges that could increase the current speeds through the openings, thereby disturbing the oyster beds. The numerical model currents were produced by a strong spring tide without a wind-induced surge. If the two were coincident or the surge was sufficiently strong, the currents could be substantially stronger behind the middle breakwater and oriented more directly toward the oyster beds. Wind waves may also play a part in the scouring of the oyster beds in this region.

42. The purpose of the previous discussion is to demonstrate the ability of the numerical model to simulate the subtle circulation patterns described by those most familiar with the harbor before any project changes were made. From this comparison the plan results can be evaluated with more confidence.

43. The plan results were generated using boundary conditions and model coefficients that were identical to the base simulation. The only difference between base and plan simulations was that a different model geometry was used. The plan condition was implemented by taking the base condition and moving nodes to describe the new horizontal locations of the channels and turning basins. Where deepening was planned, the node elevations were lowered.

44. Both base and plan simulations consisted of thirty-six 0.5-hr time-steps that corresponded to boundary conditions collected between 0000 and 1800 eastern standard time (EST) on 16 June 1987. Hours 0000 to 0430 served as spin-up time to allow model stability. Hours 0500 to 1800 represented a complete tidal cycle simulation. Vector plots displaying current

velocities through time are shown in Plates 1-28. Plates 1-14 are for the base condition while Plates 15-28 are for the plan condition. Although computations were made at 0.5-hr intervals, the data presented in the report are given at 1.0-hr intervals.

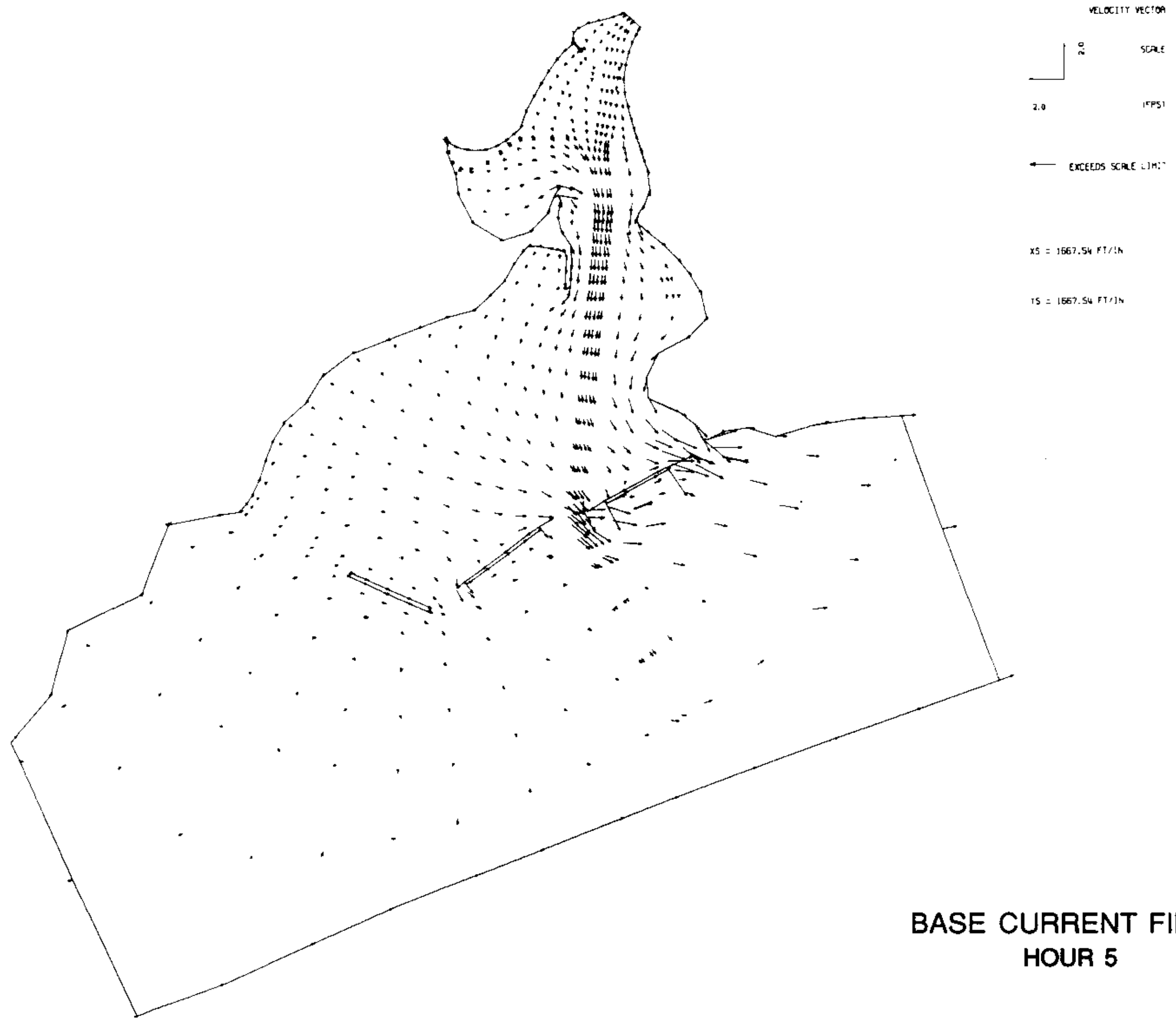
45. The differences between base and plan circulation were determined using base-minus-plan vector plots (Plates 29-42). The difference plots show vectors that were computed by subtracting the x- and y-components of the plan from those of the base. As long as the node locations were the same in both base and plan, the difference plots provide a good indication of base-minus-plan differences. However, where nodes were moved to depict the plan condition, the plots are less meaningful. That is the case with several nodes on the edges of the navigation channel at Southwest Ledge, between the breakwaters, and in the turning basin in the inner harbor. It should also be noted that the differences are plotted at a much larger scale than in Plates 1-28.

46. Overall, the differences between base and plan conditions were quite small. There is no indication that there will be any change in circulation patterns that should be alarming to pilots or fishermen. For almost all of the regions that were defined as being productive oyster grounds, the base-to-plan differences were less than 0.1 fps. The areas where differences were larger than 0.1 fps were those areas within the deepened channels. In the channels, the plan condition exhibited slightly lower current speeds, so navigation would not be adversely affected.

PART VI: CONCLUSIONS

47. Numerical model simulations of the base and plan conditions in New Haven Harbor indicate that the proposed navigation improvements will have little effect on tidal circulation in the harbor. In areas defined as productive oyster beds, differences in current speeds were almost always less than 0.1 fps with no significant change in current direction. Slightly larger differences occurred in the navigation channels, with the plan condition having lower current velocities.

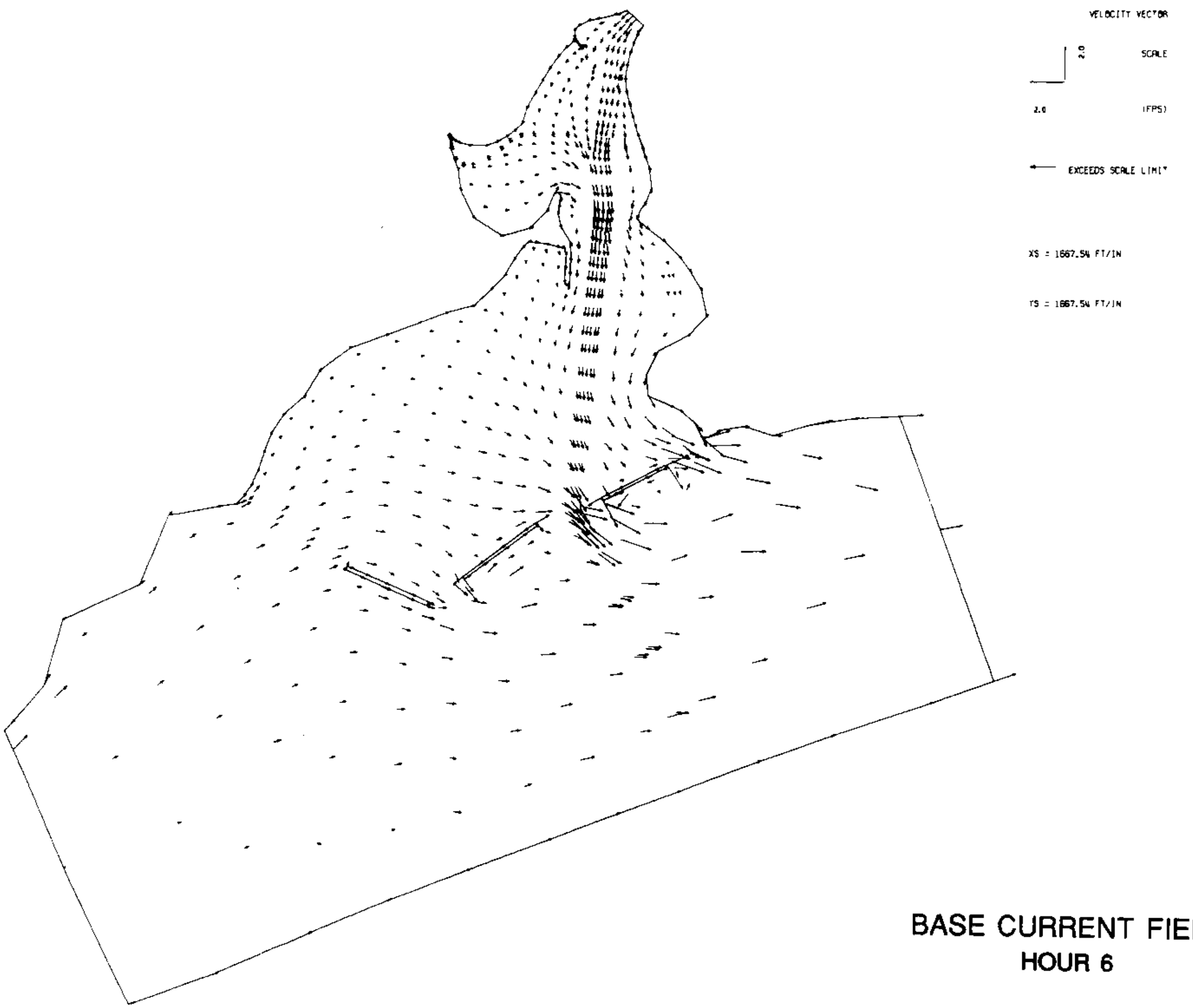
48. Base and plan hydrodynamic data sets were produced with the numerical model that will be useful in future ship simulation studies. The results successfully reproduced the variable current magnitudes and directions in the navigation channel, which are important for good ship simulation studies.



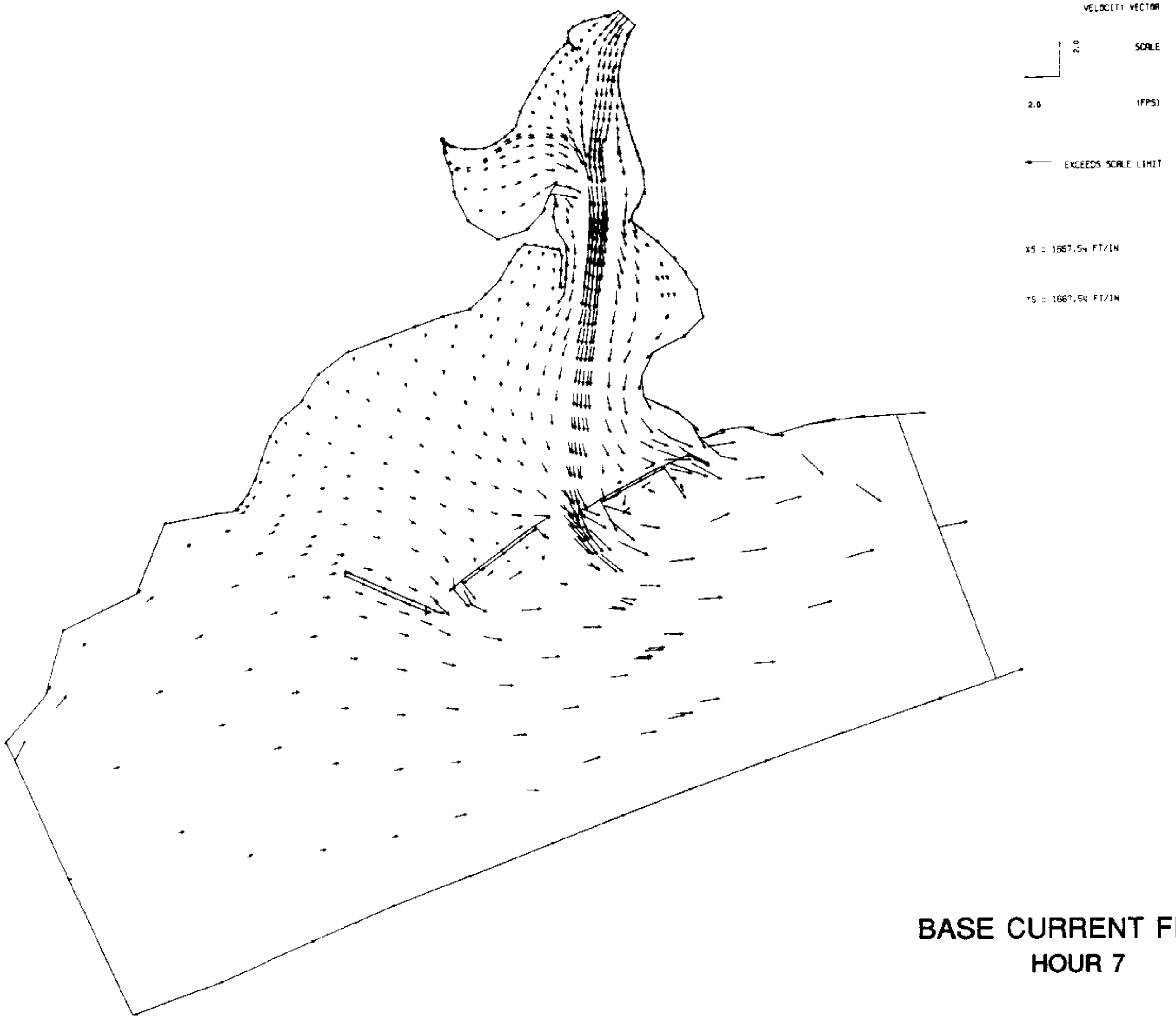
BASE CURRENT FIELD
HOUR 5

PLATE 1

PLATE 2



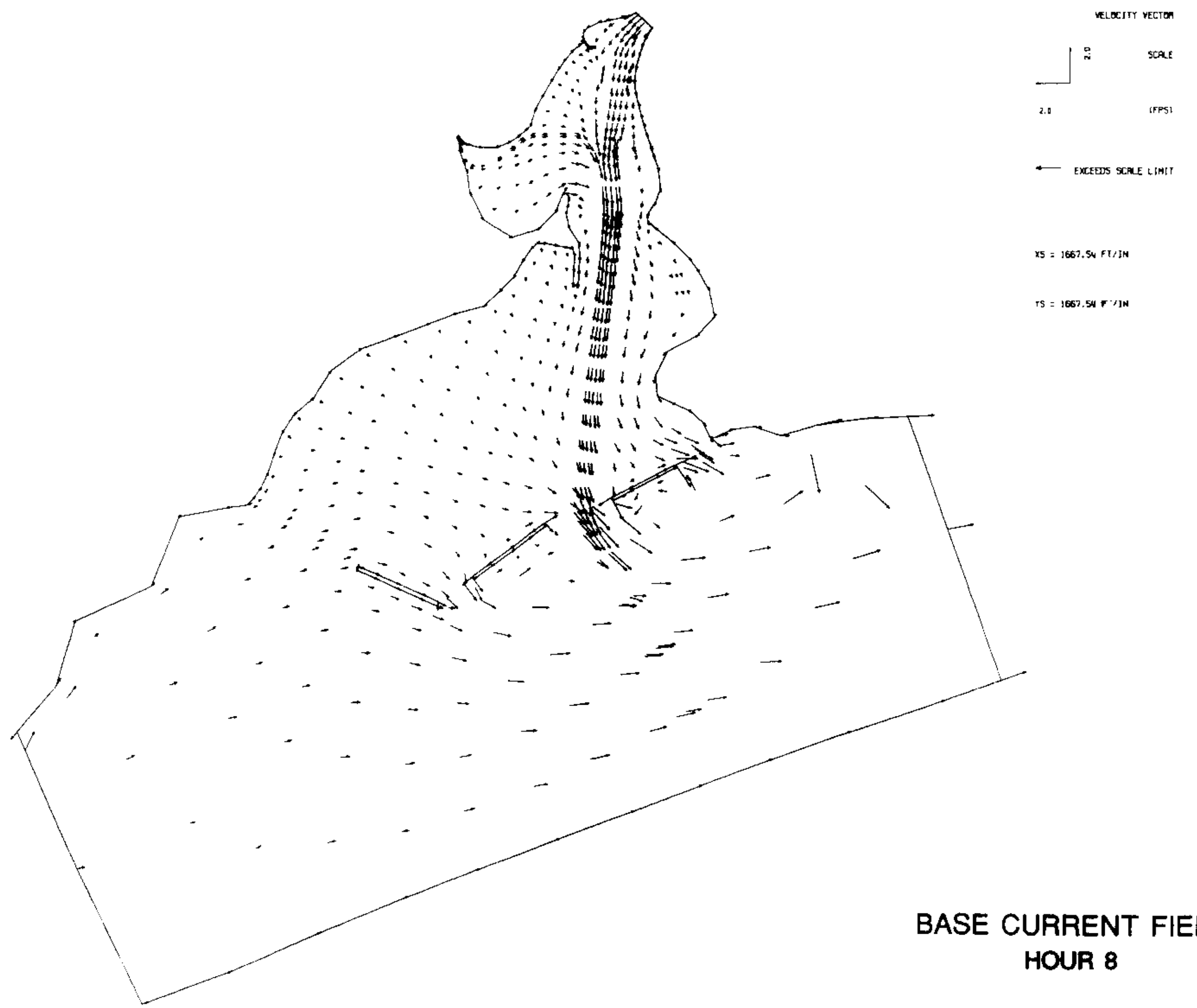
BASE CURRENT FIELD
HOUR 6



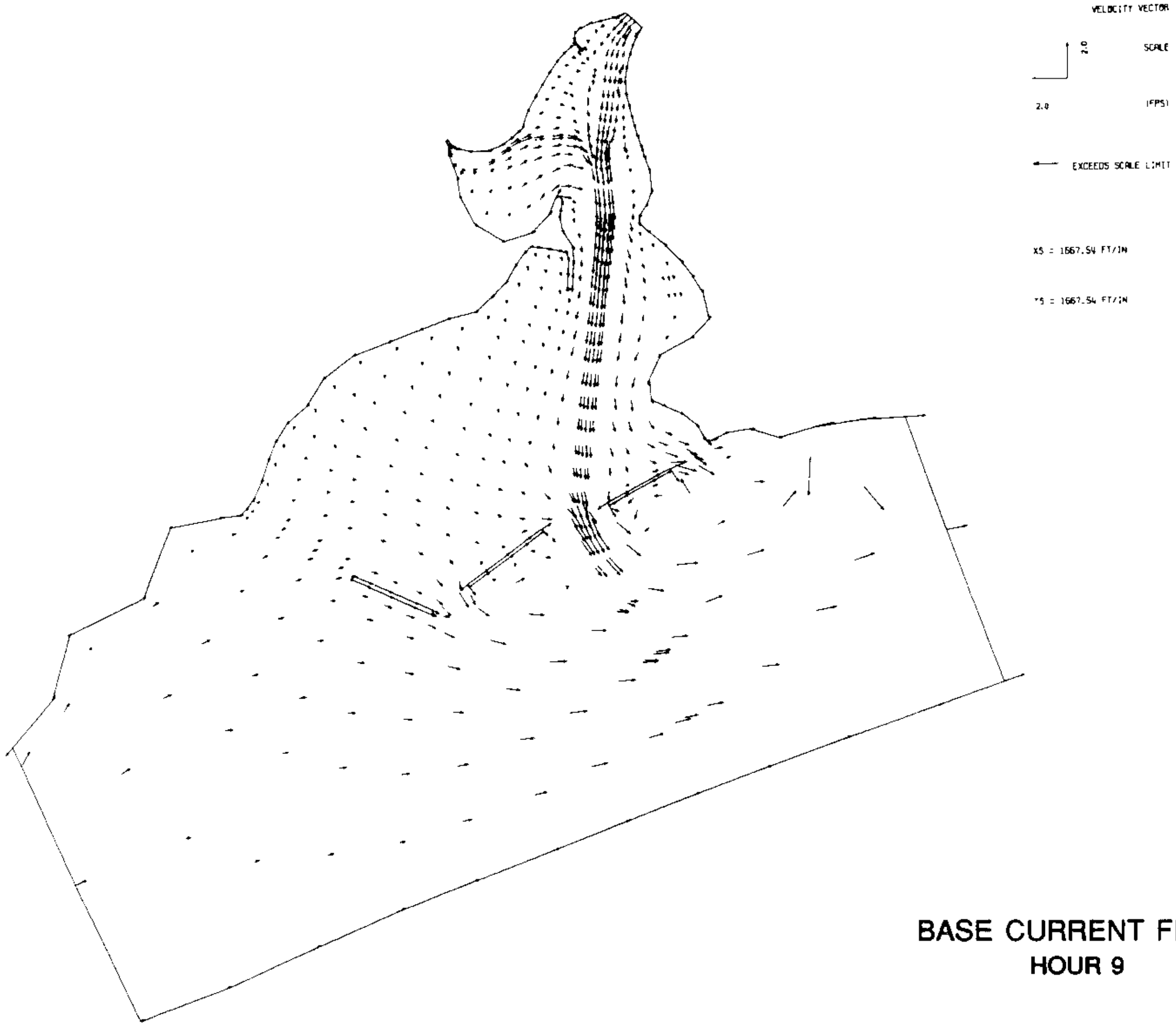
BASE CURRENT FIELD
HOUR 7

PLATE 3

PLATE 4



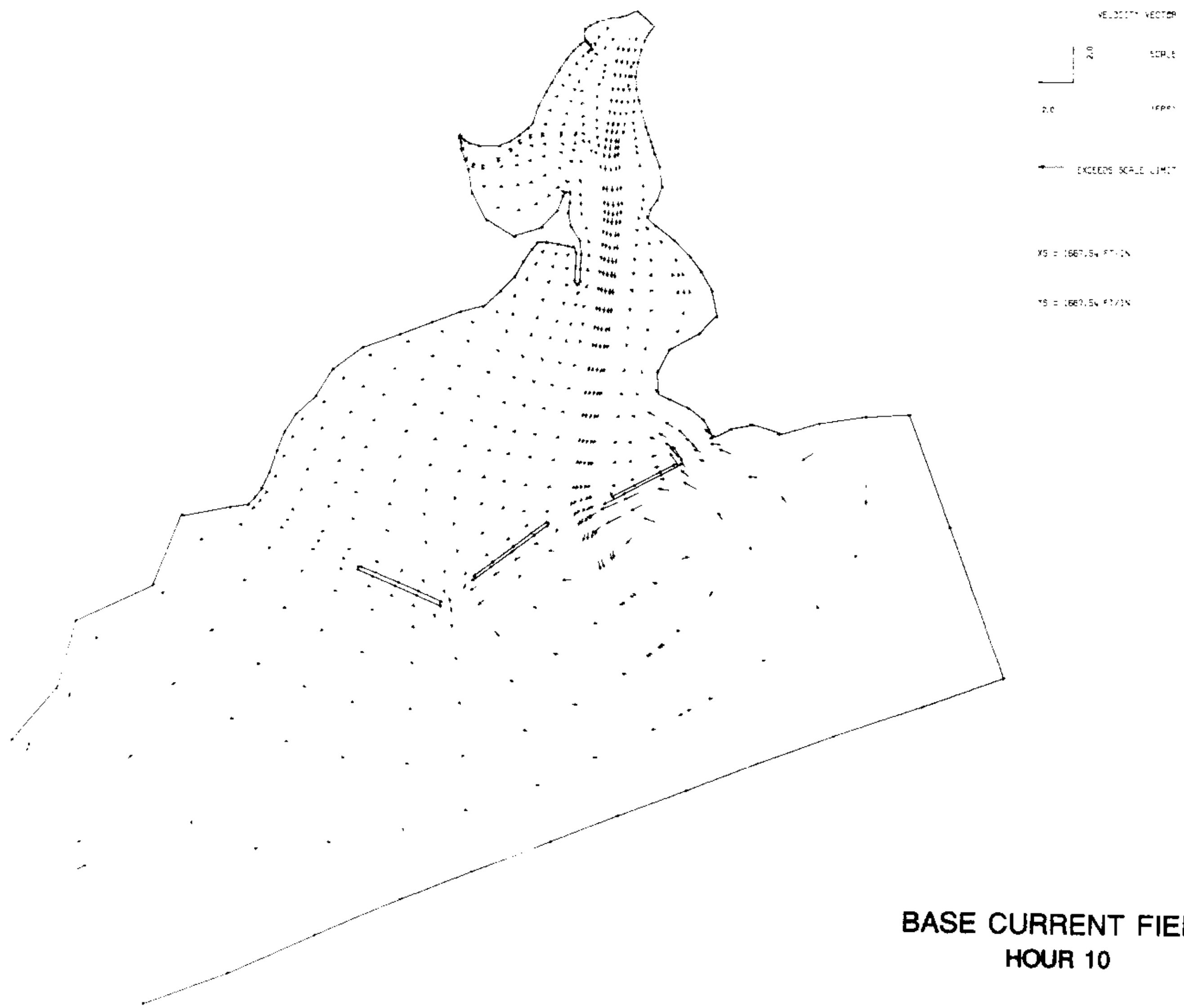
BASE CURRENT FIELD
HOUR 8



BASE CURRENT FIELD
HOUR 9

PLATE 5

PLATE 6



BASE CURRENT FIELD
HOUR 10

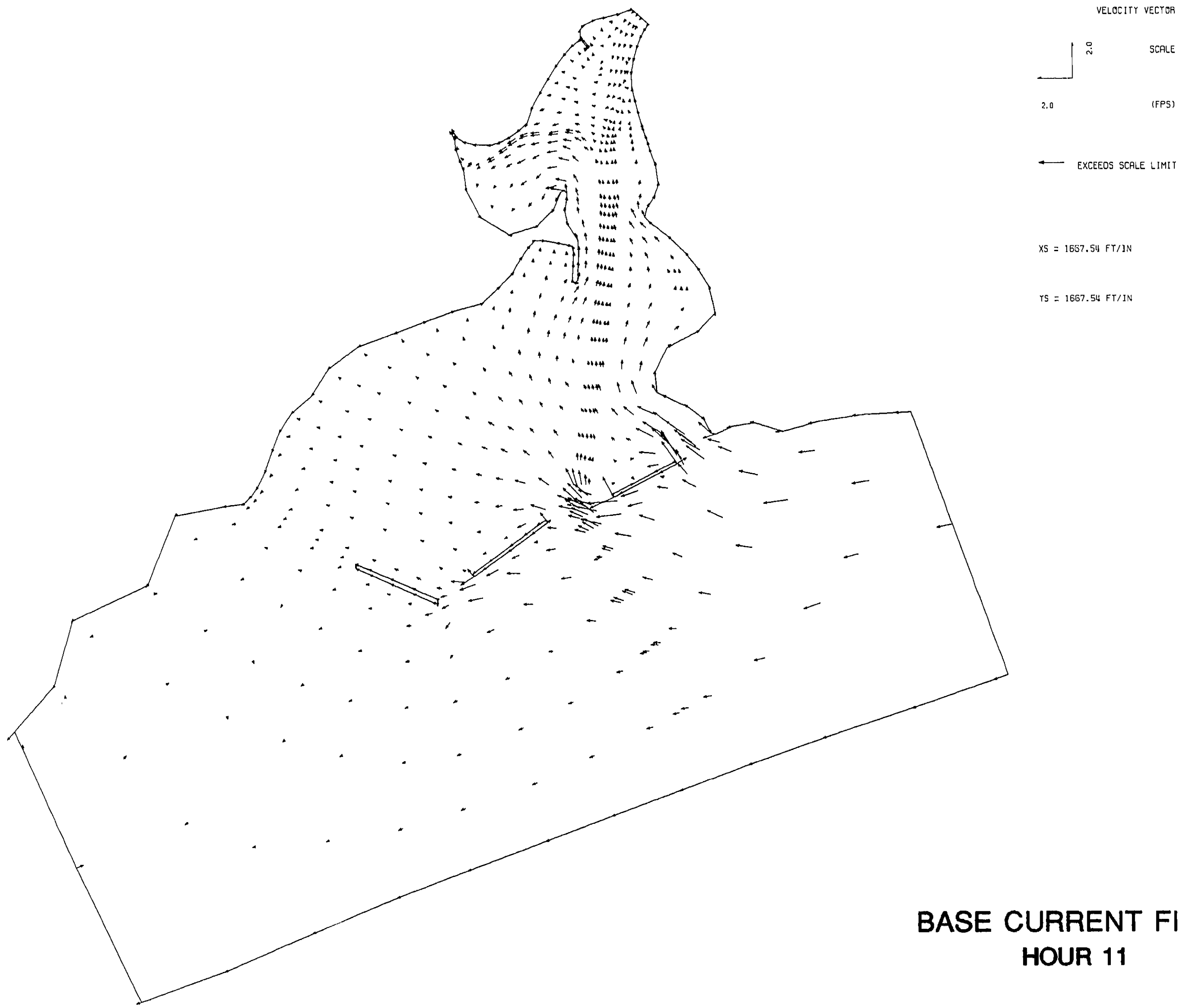
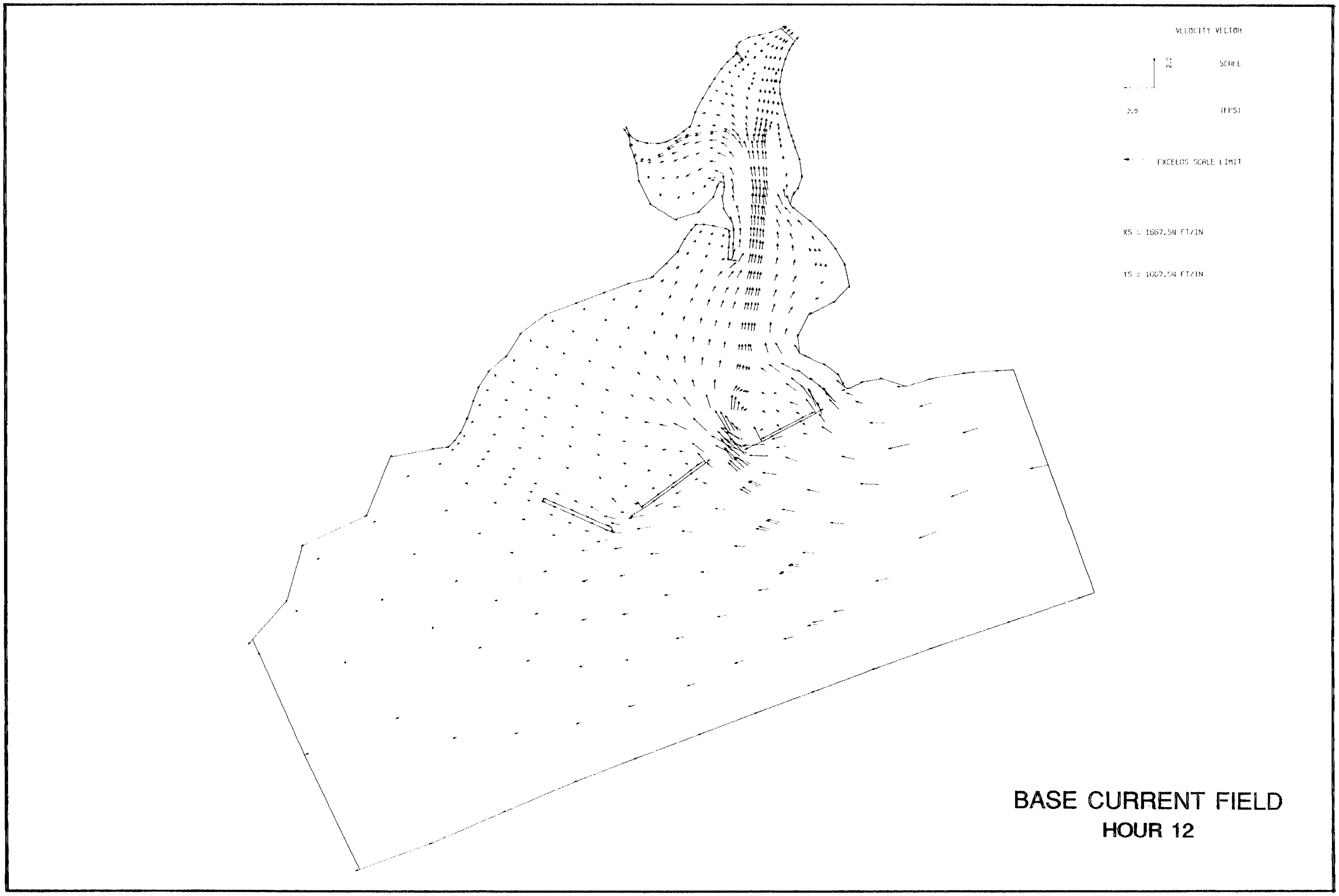


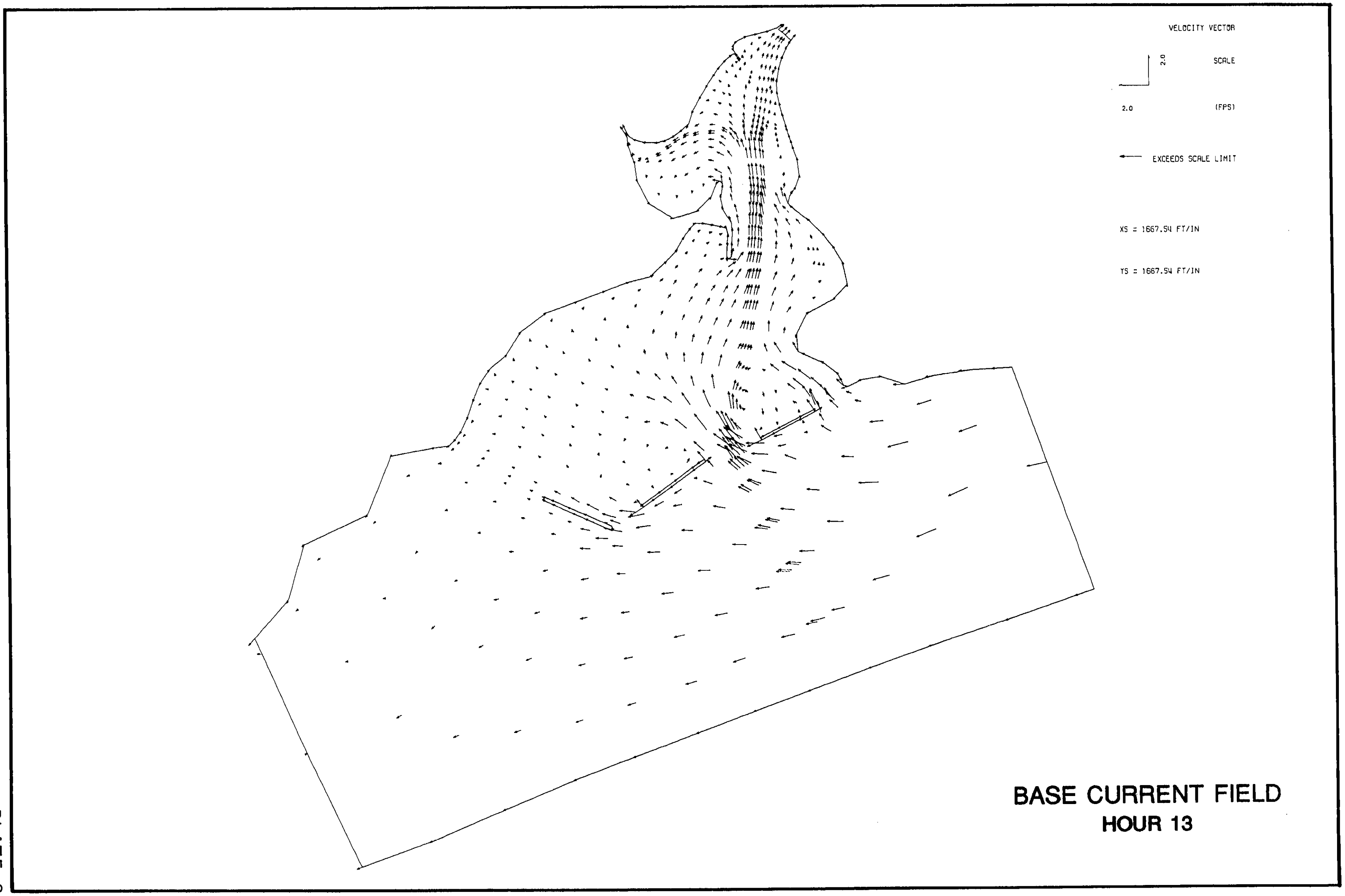
PLATE 7

BASE CURRENT FIELD
HOUR 11

PLATE 8



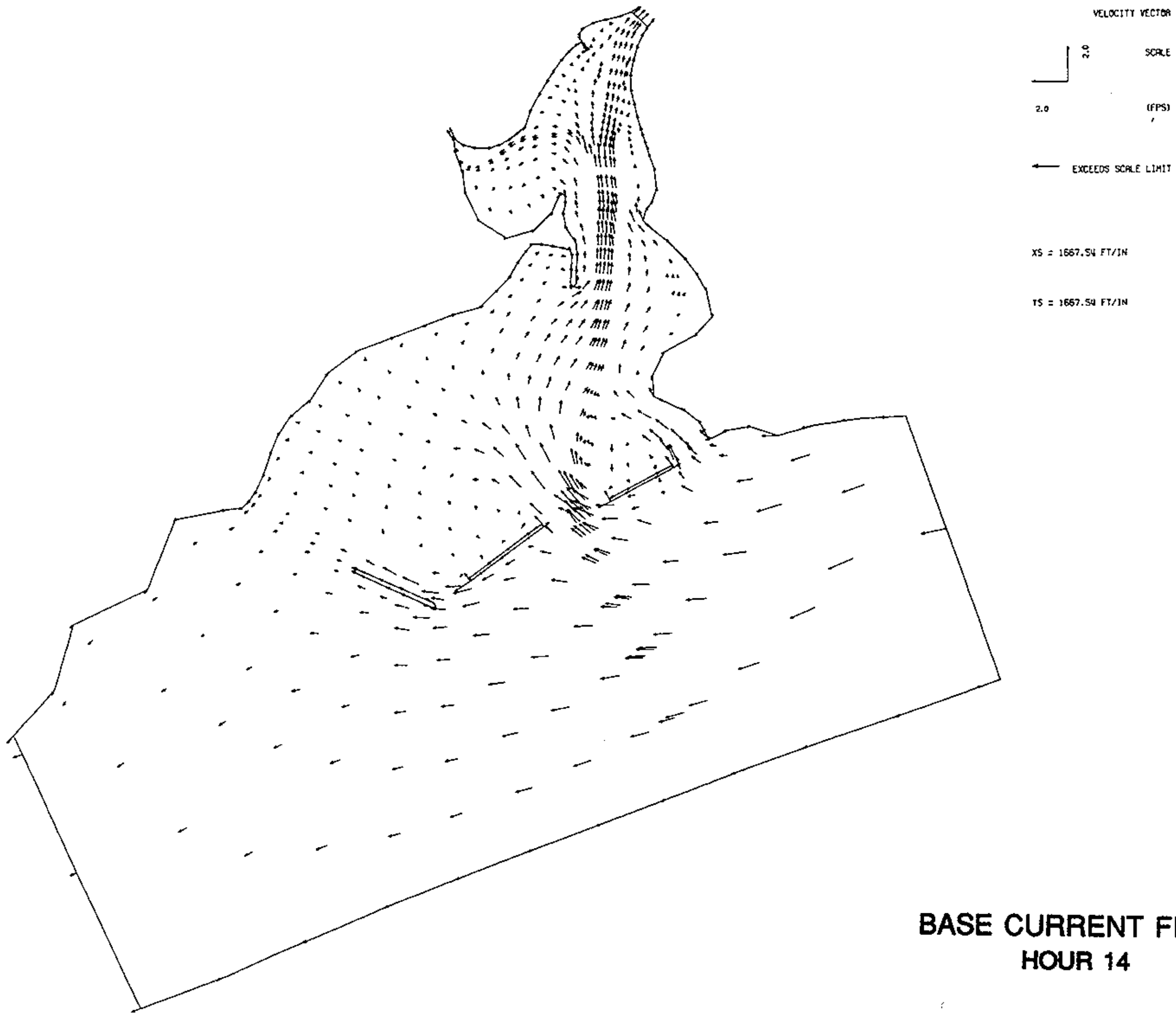
BASE CURRENT FIELD
HOUR 12



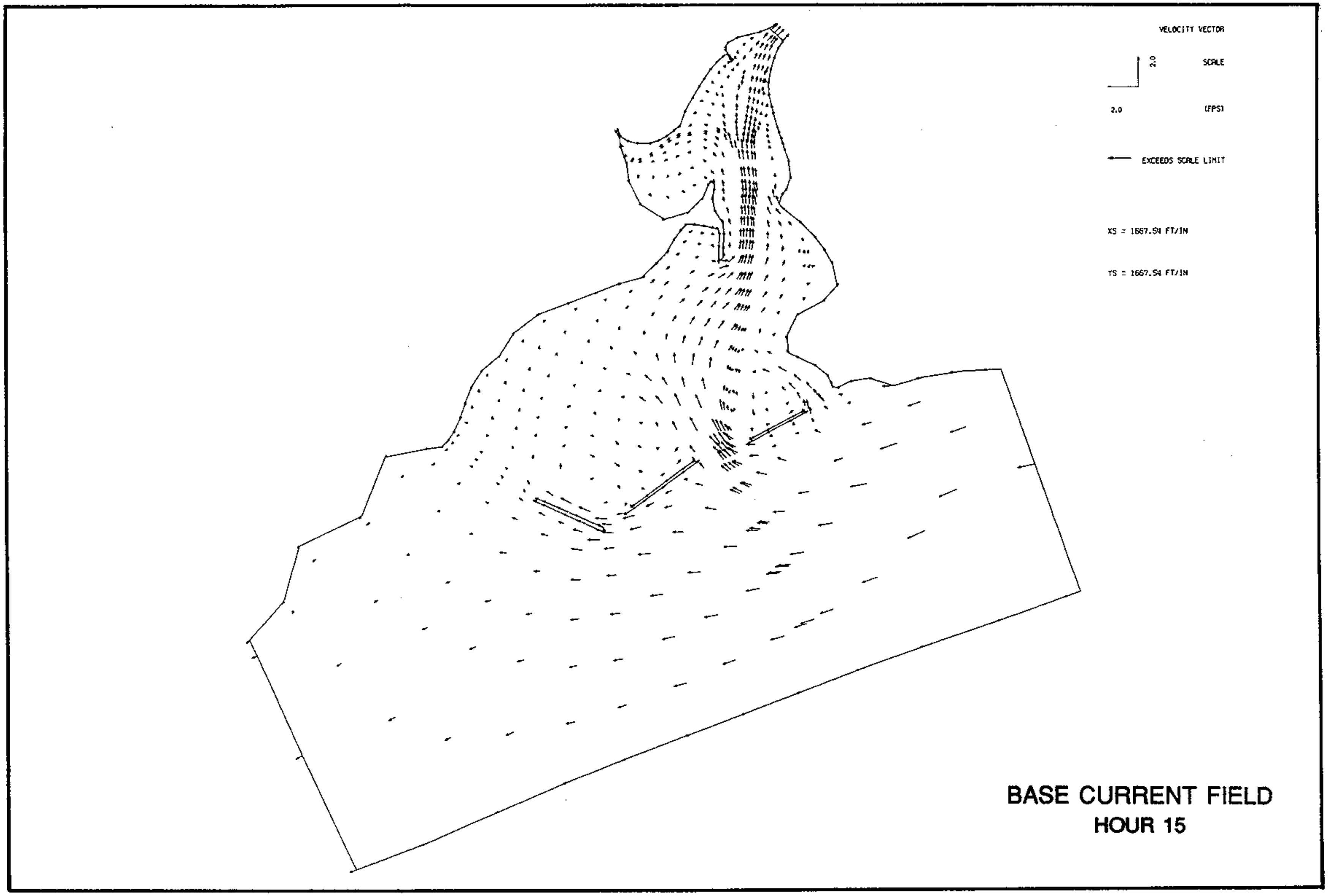
BASE CURRENT FIELD
HOUR 13

PLATE 9

PLATE 10



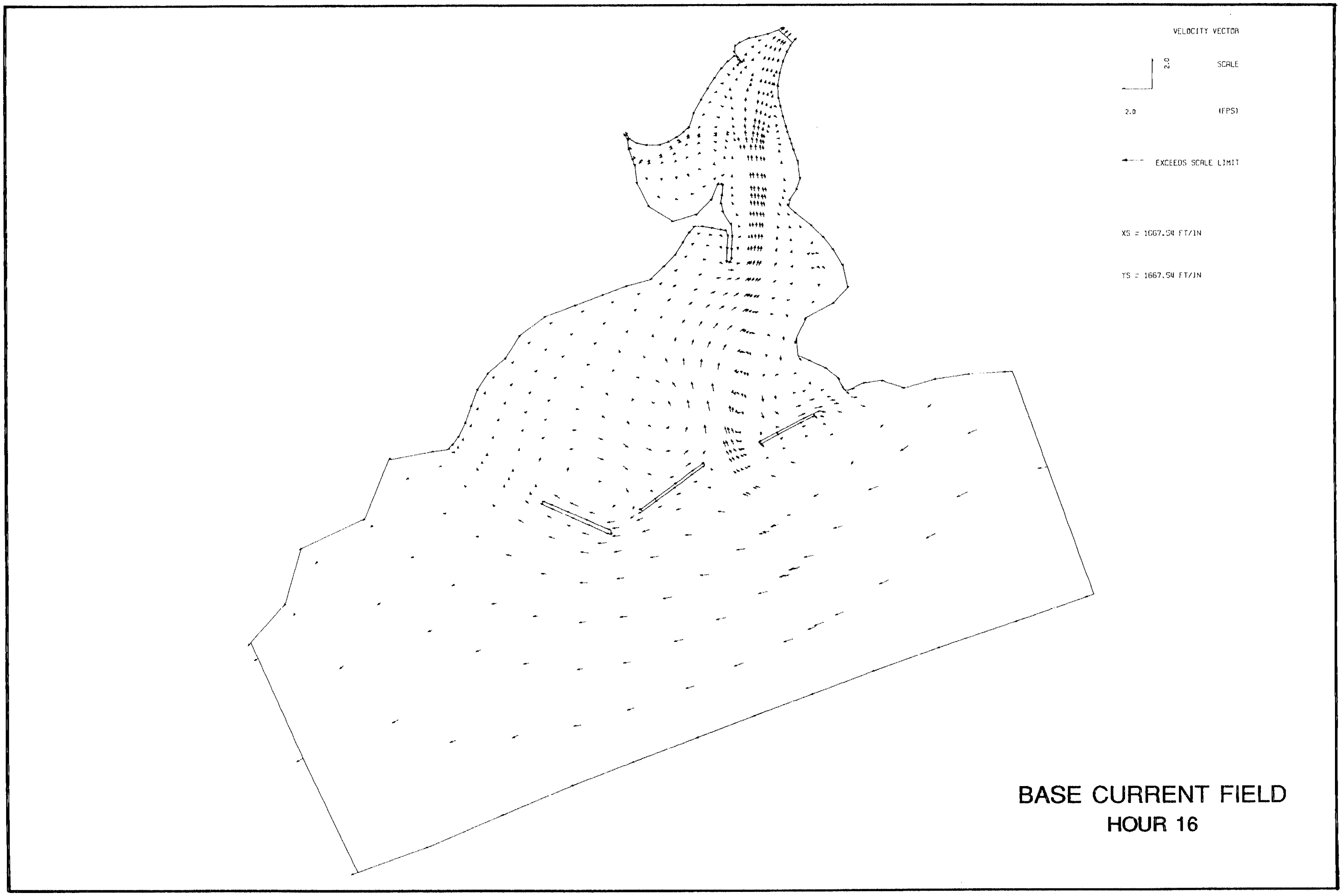
BASE CURRENT FIELD
HOUR 14



BASE CURRENT FIELD
HOUR 15

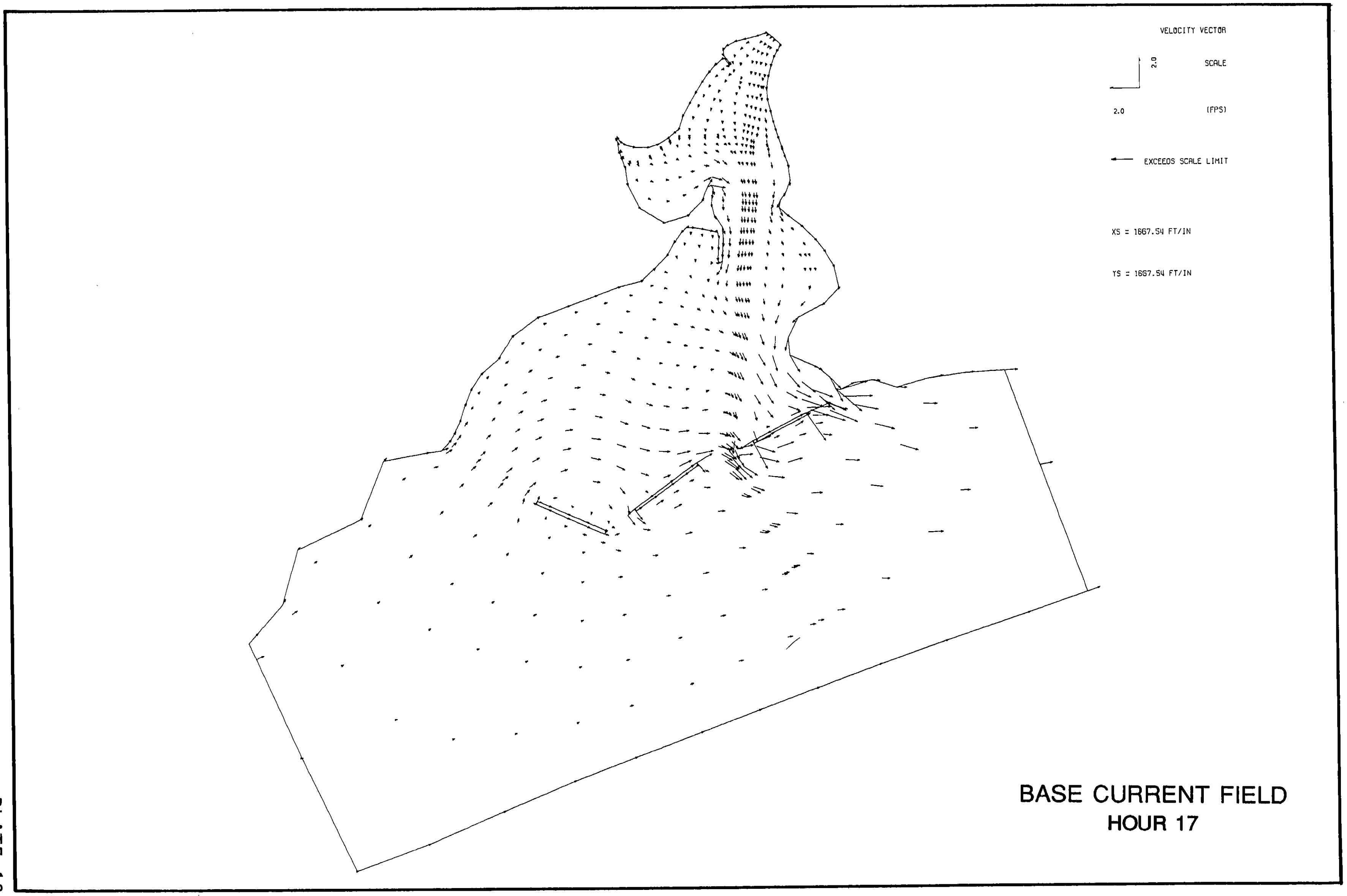
PLATE 11

PLATE 12



BASE CURRENT FIELD

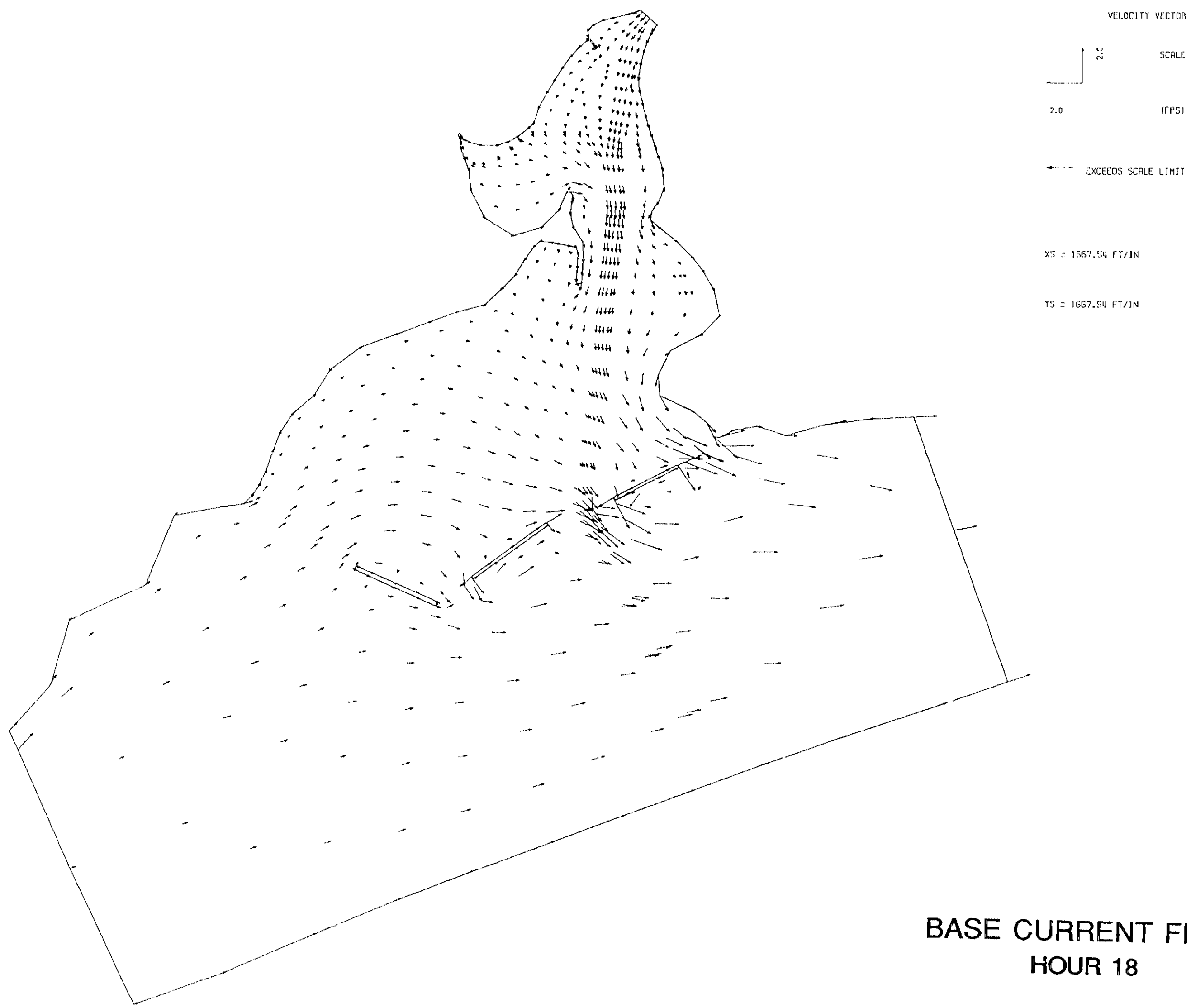
HOUR 16



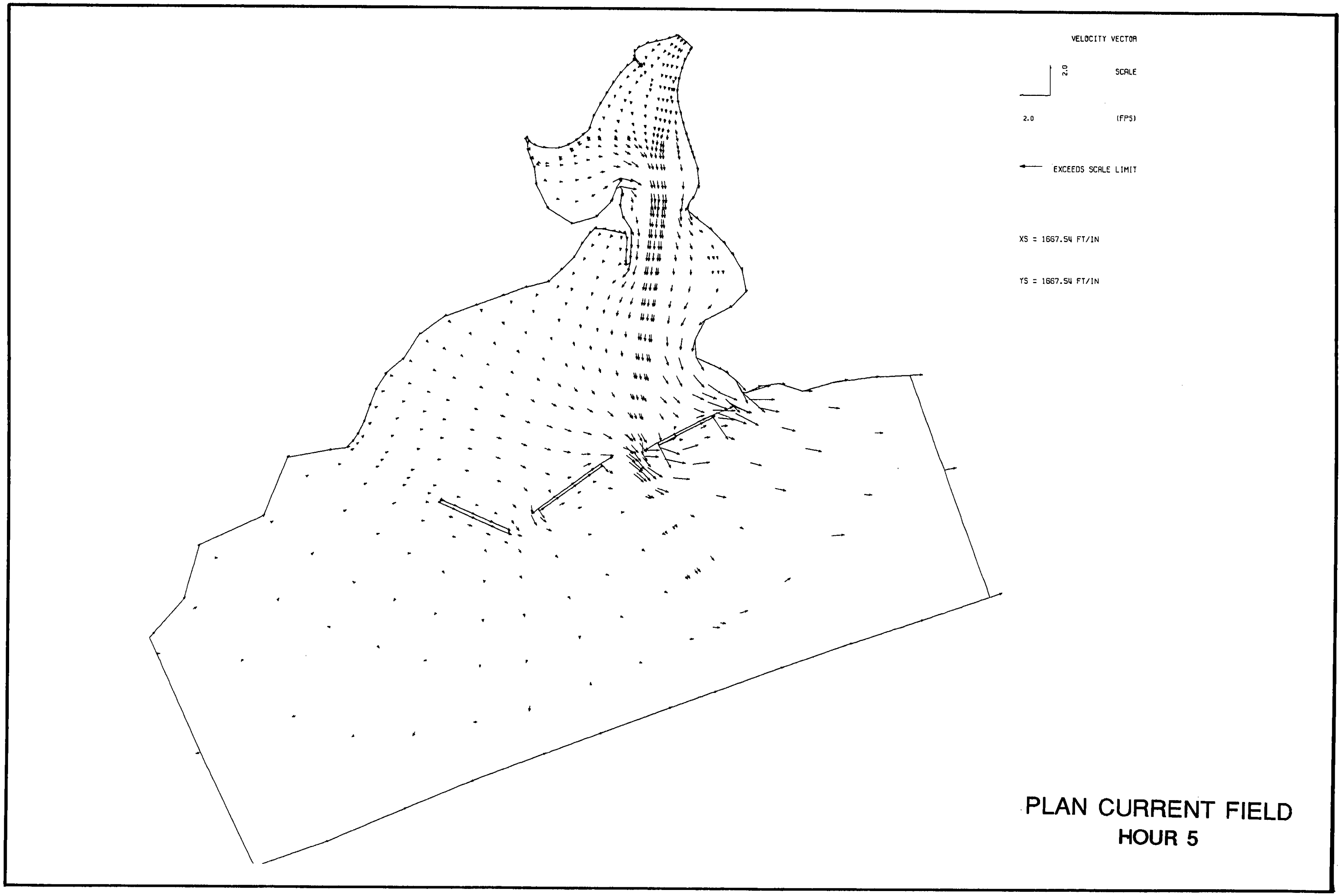
BASE CURRENT FIELD
HOUR 17

PLATE 13

PLATE 14

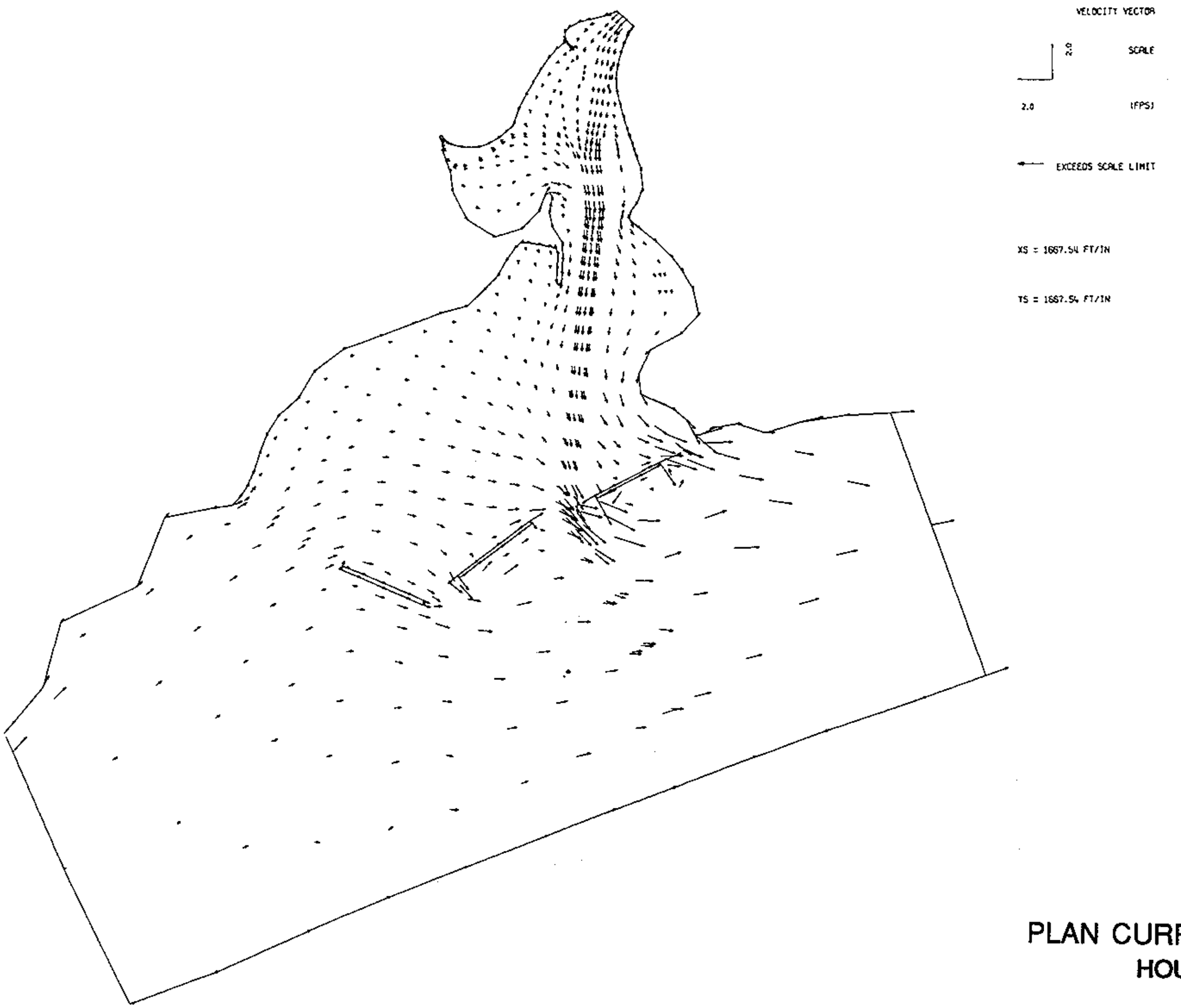


BASE CURRENT FIELD
HOUR 18

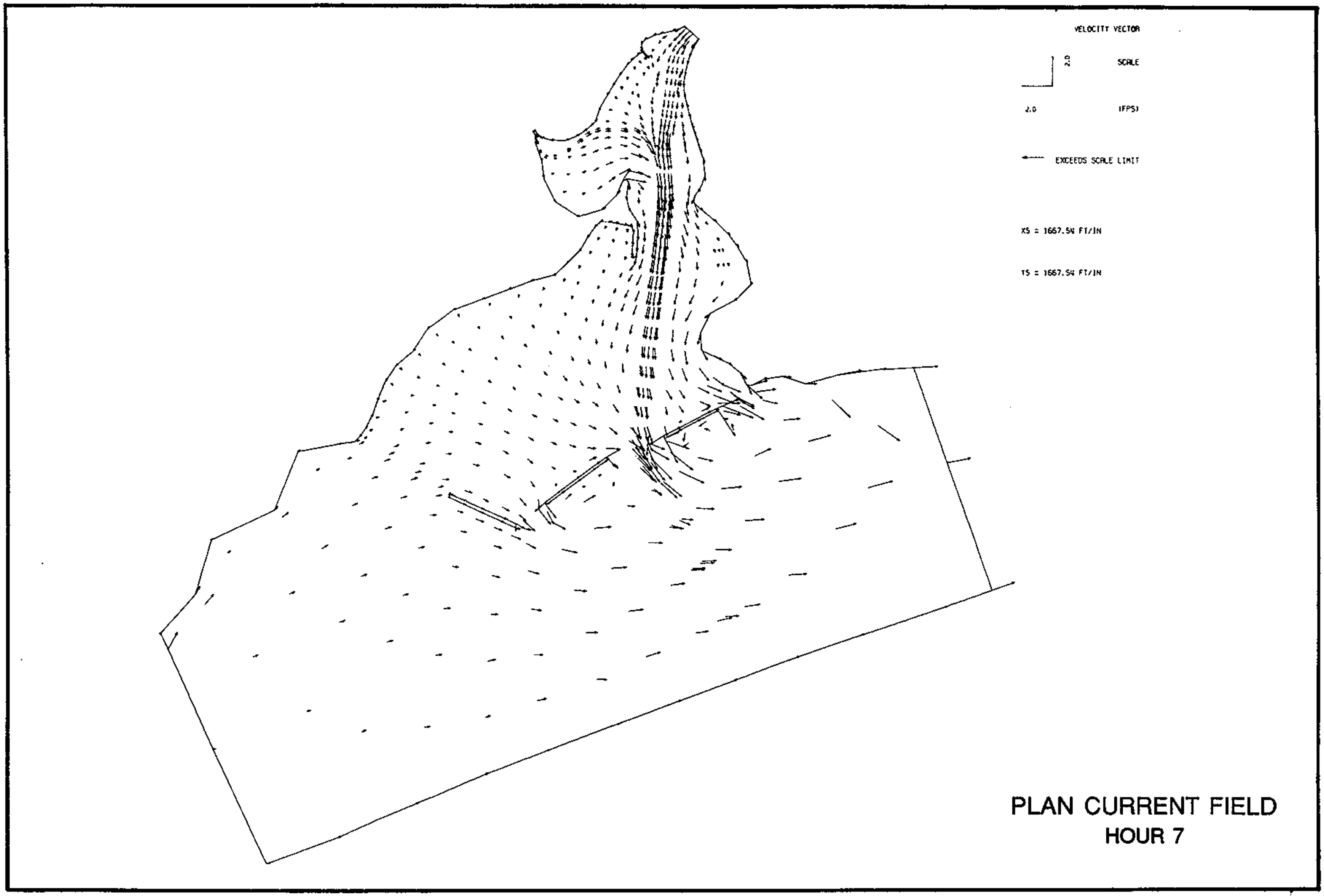


PLAN CURRENT FIELD
HOUR 5

PLATE 16



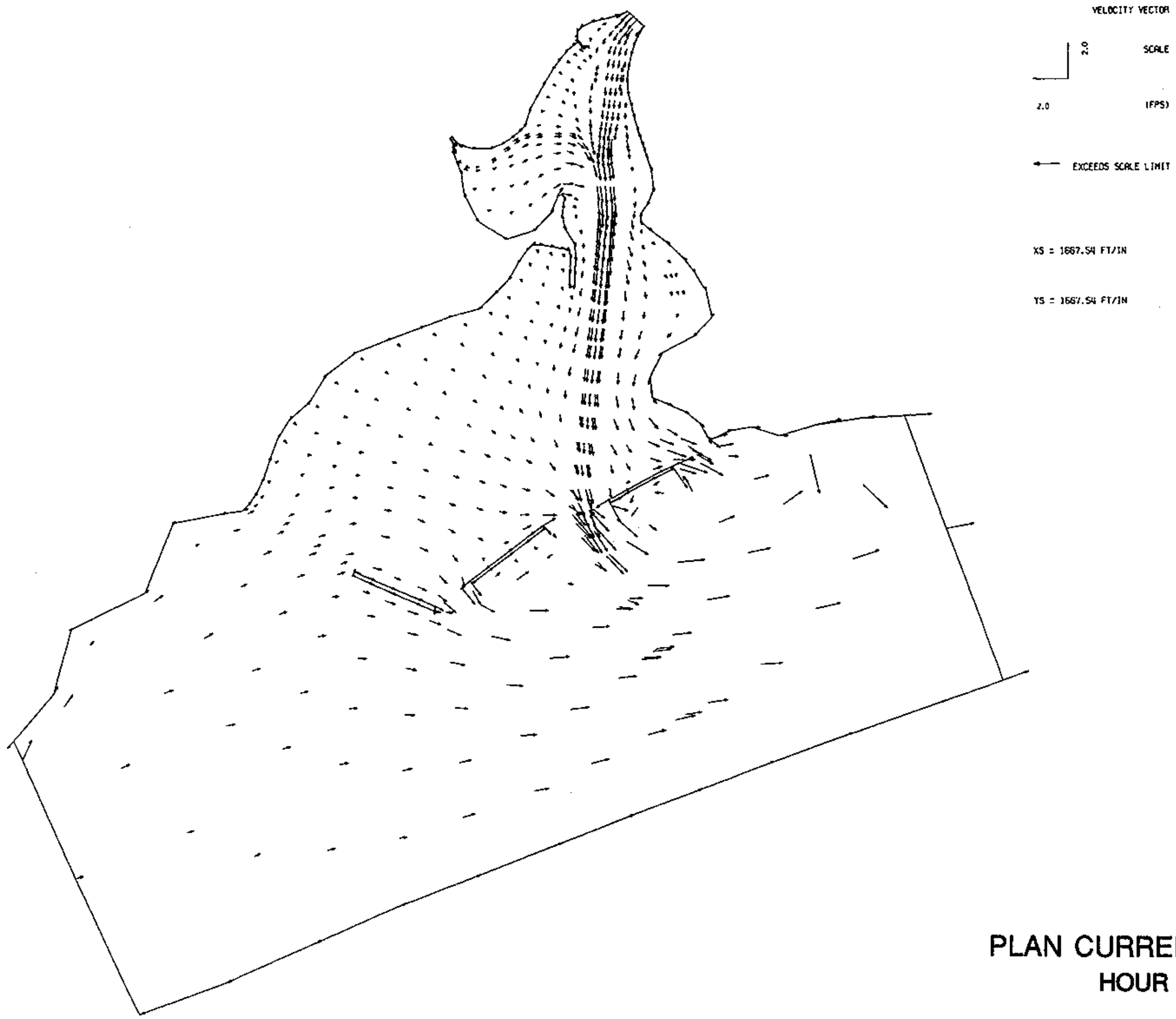
PLAN CURRENT FIELD
HOUR 6



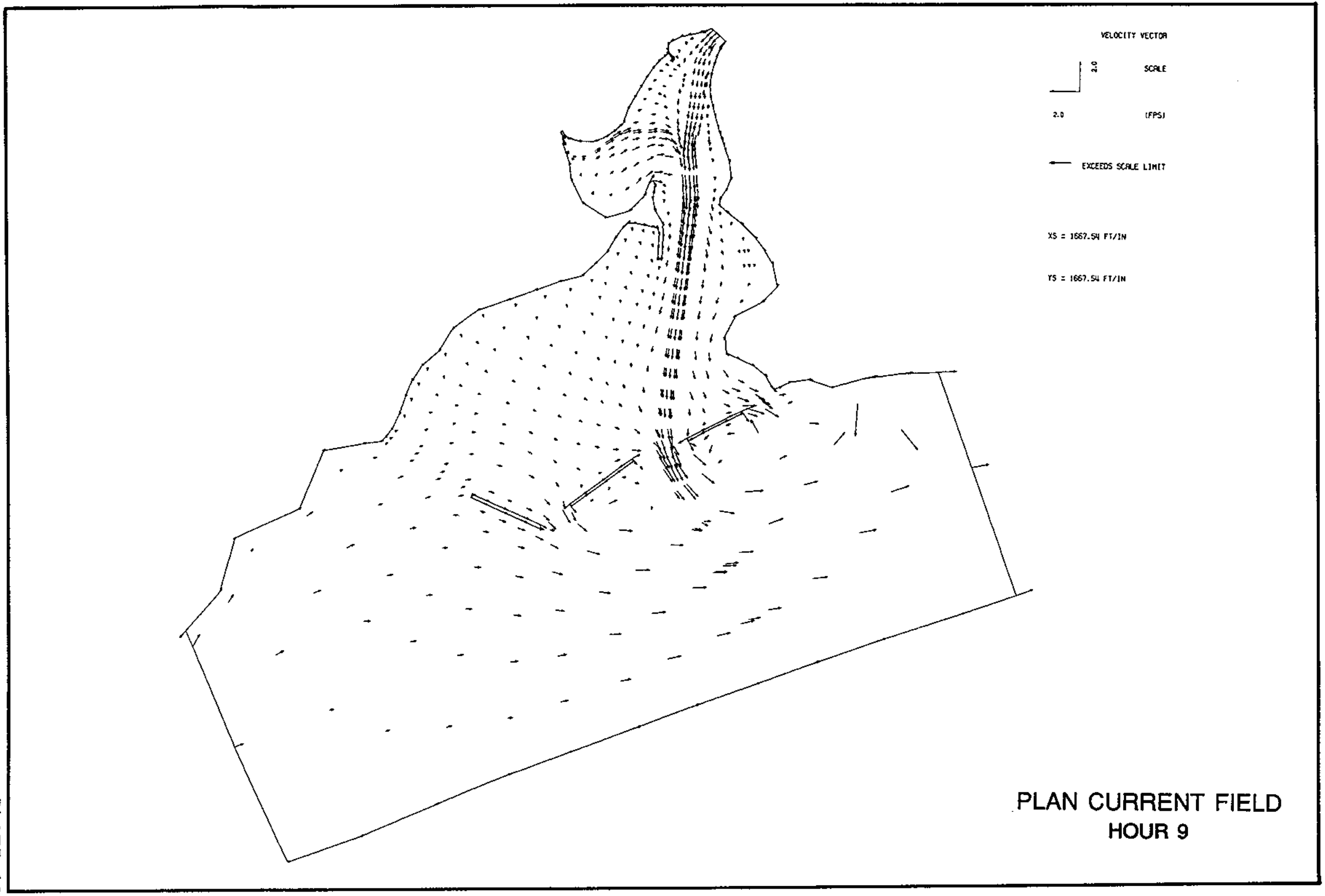
PLAN CURRENT FIELD
HOUR 7

PLATE 17

PLATE 18



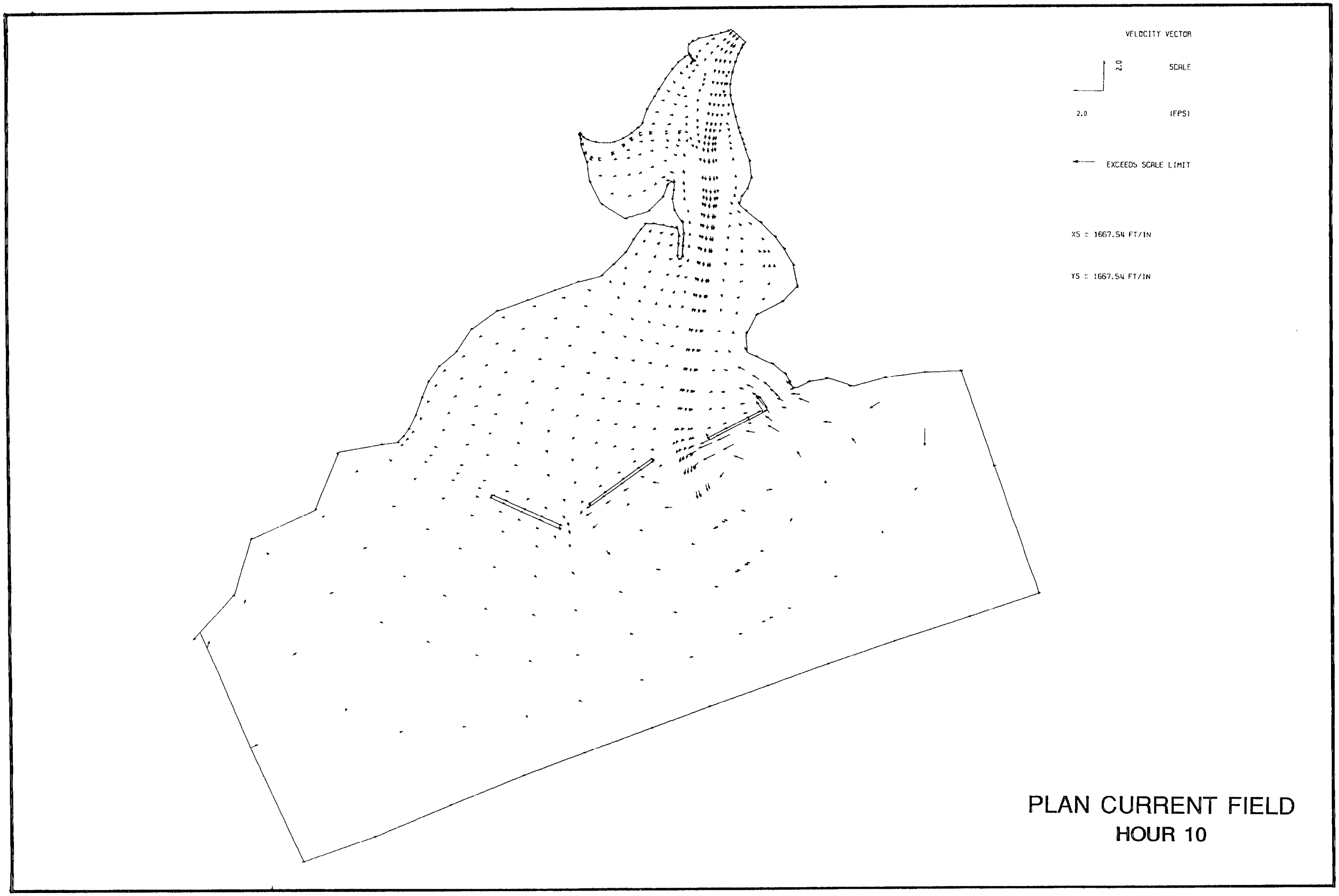
PLAN CURRENT FIELD
HOUR 8



PLAN CURRENT FIELD
HOUR 9

PLATE 19

PLATE 20



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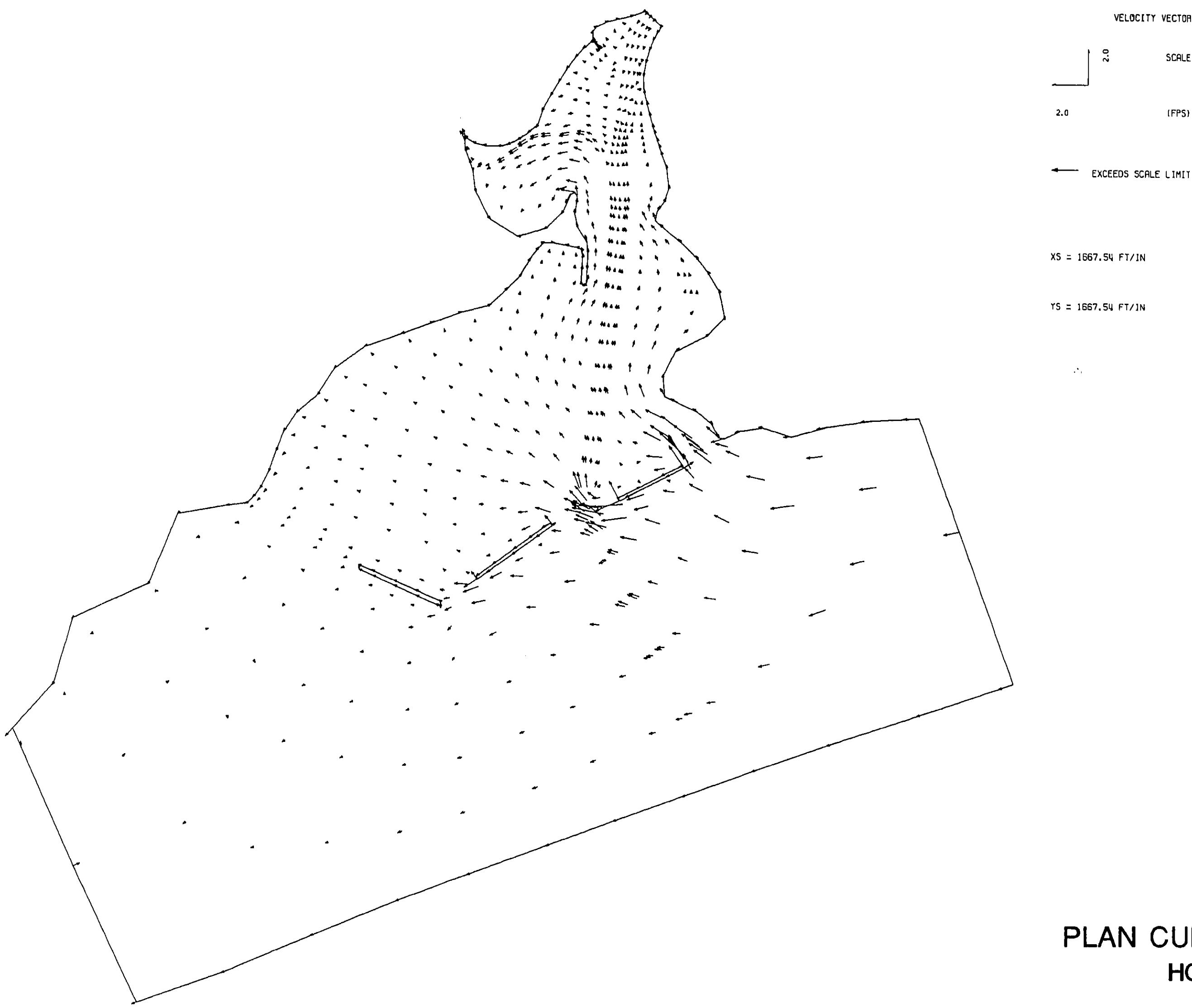

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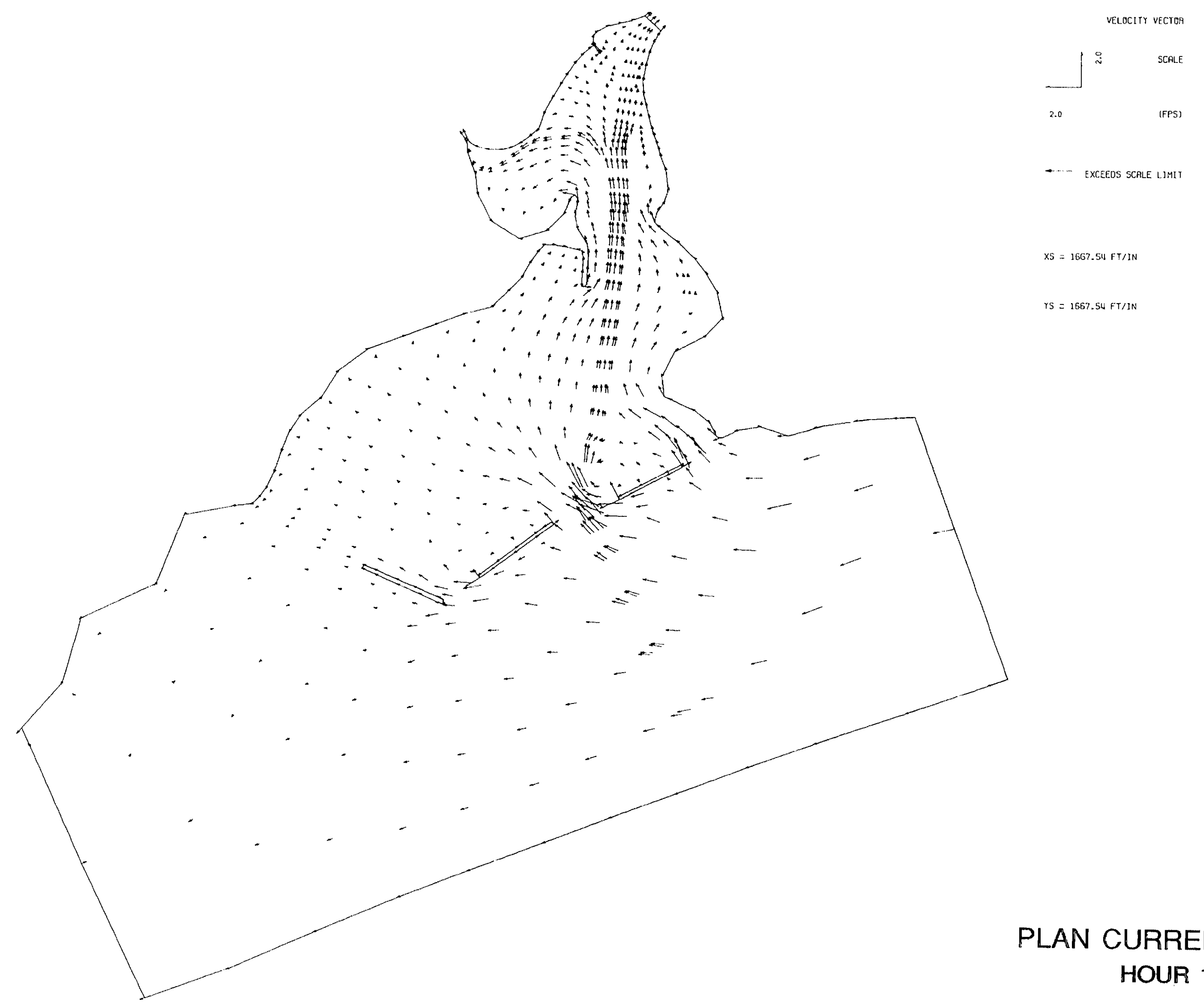

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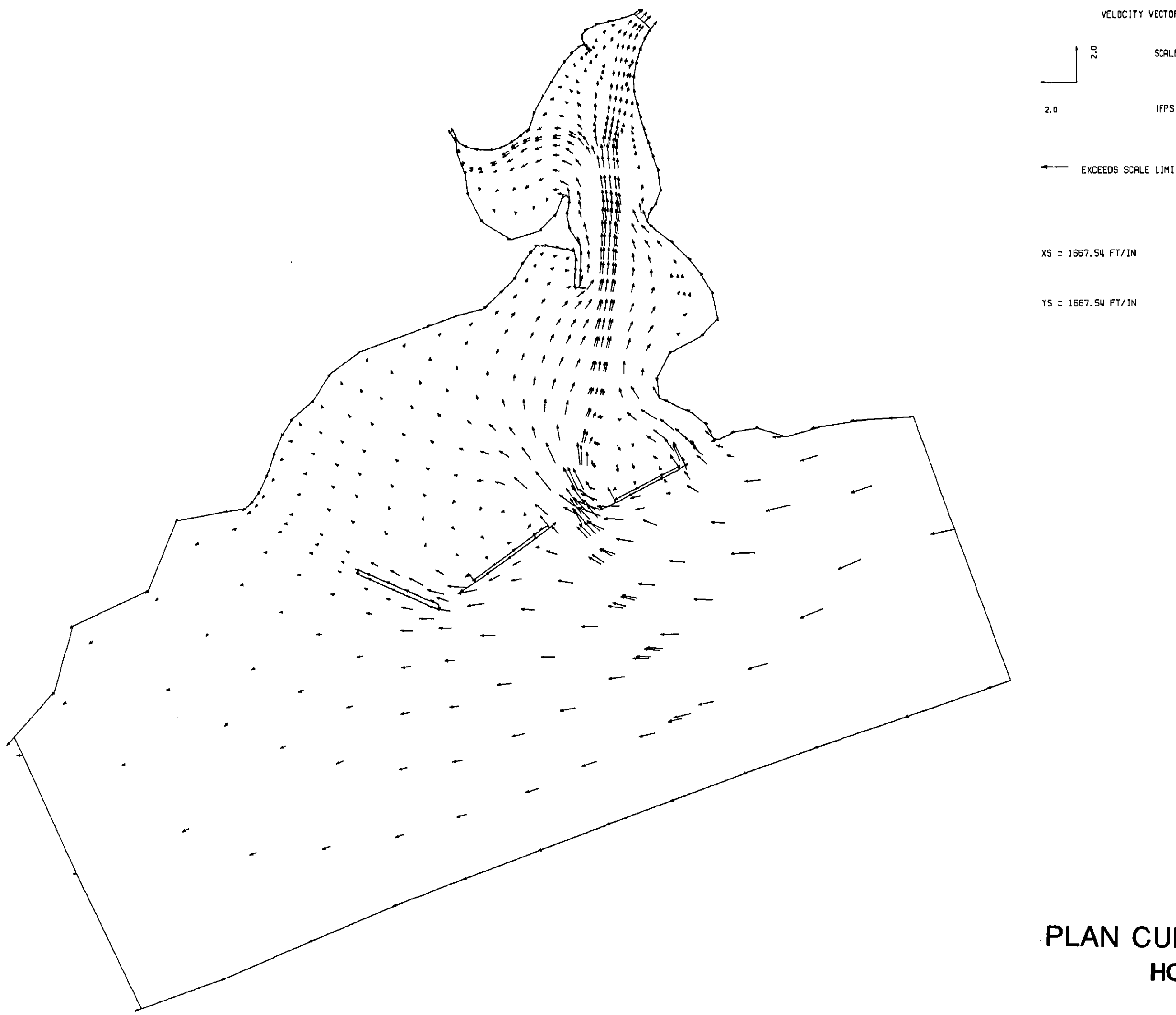

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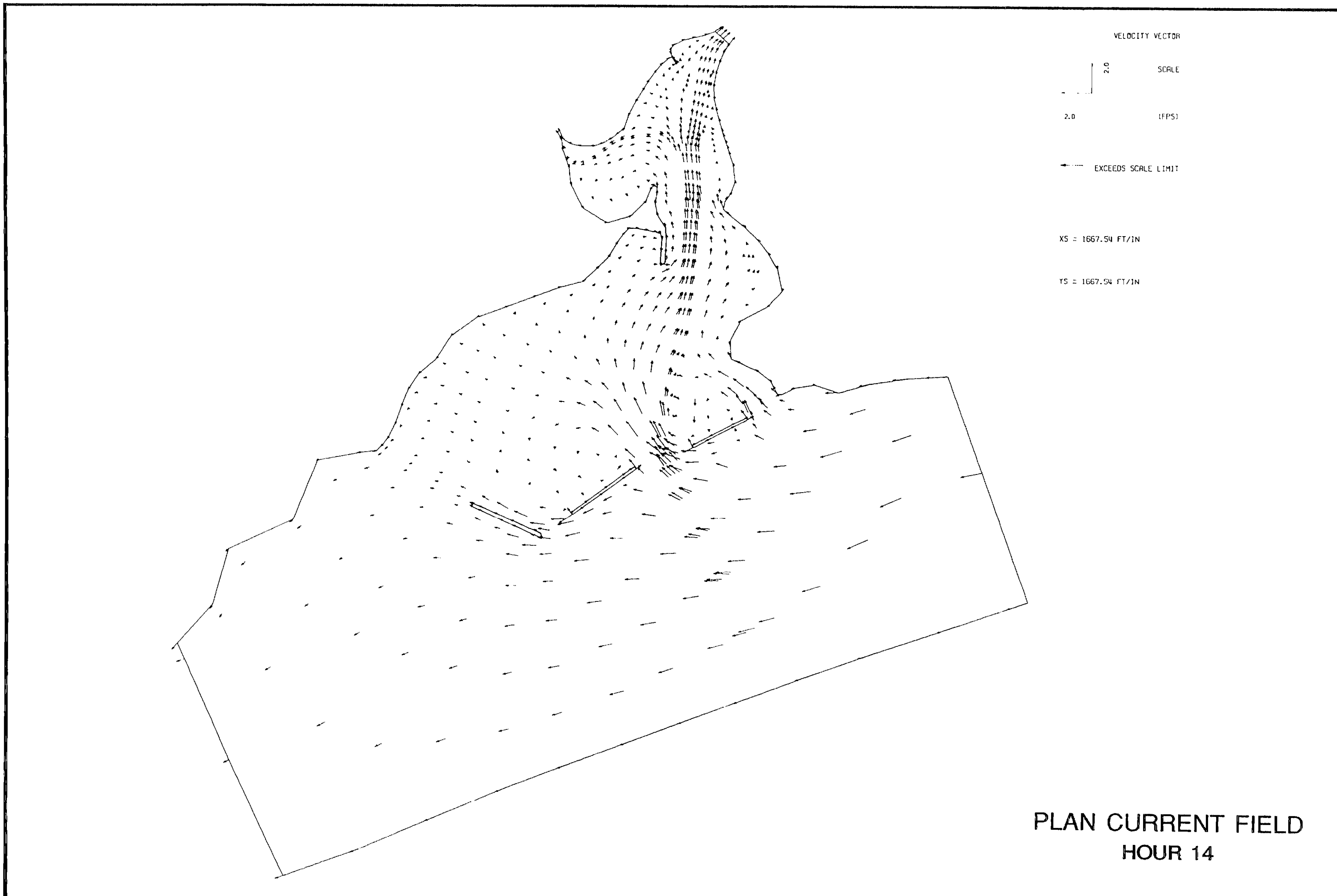

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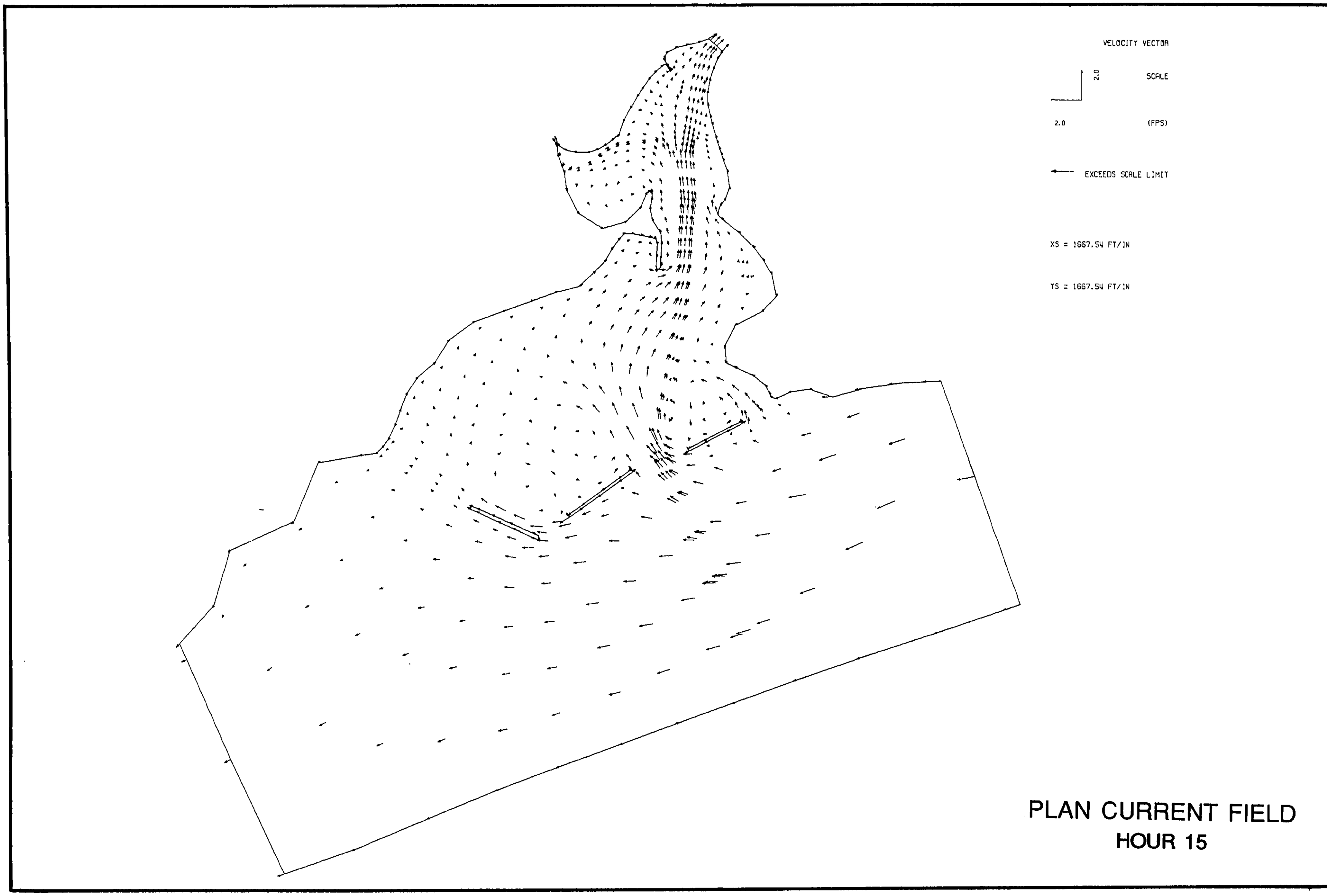
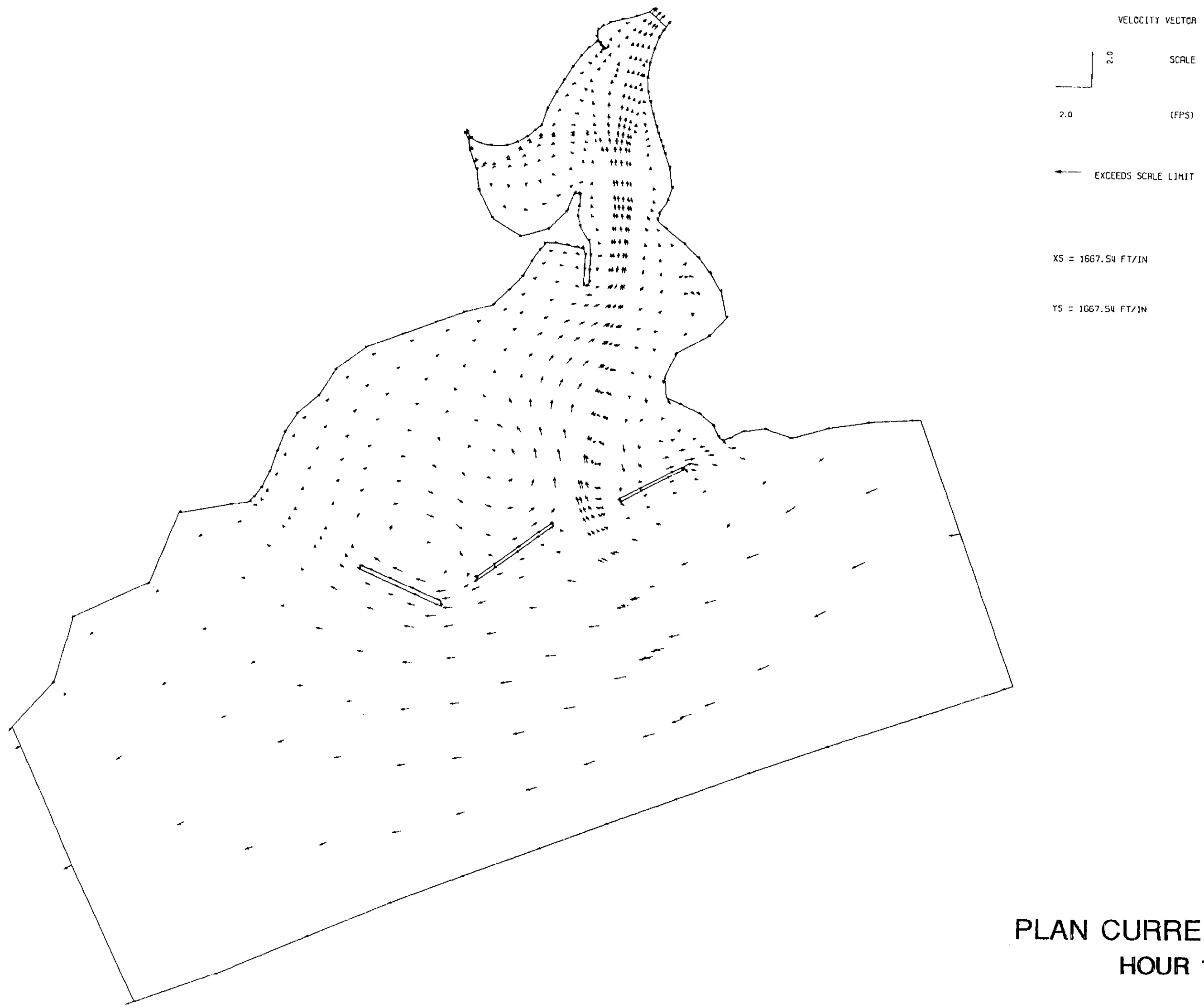


PLAN CURRENT FIELD
HOUR 15

PLATE 26



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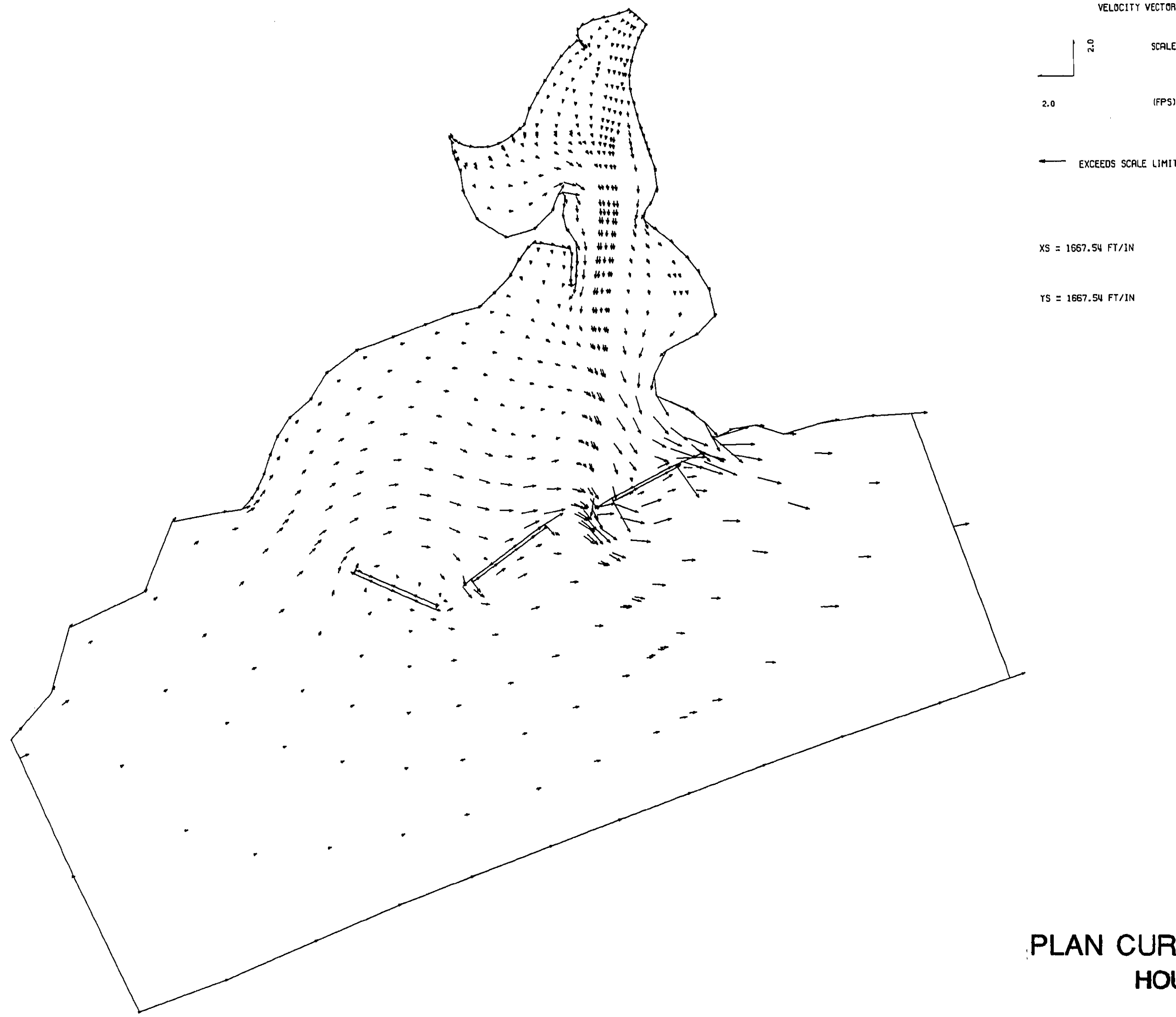
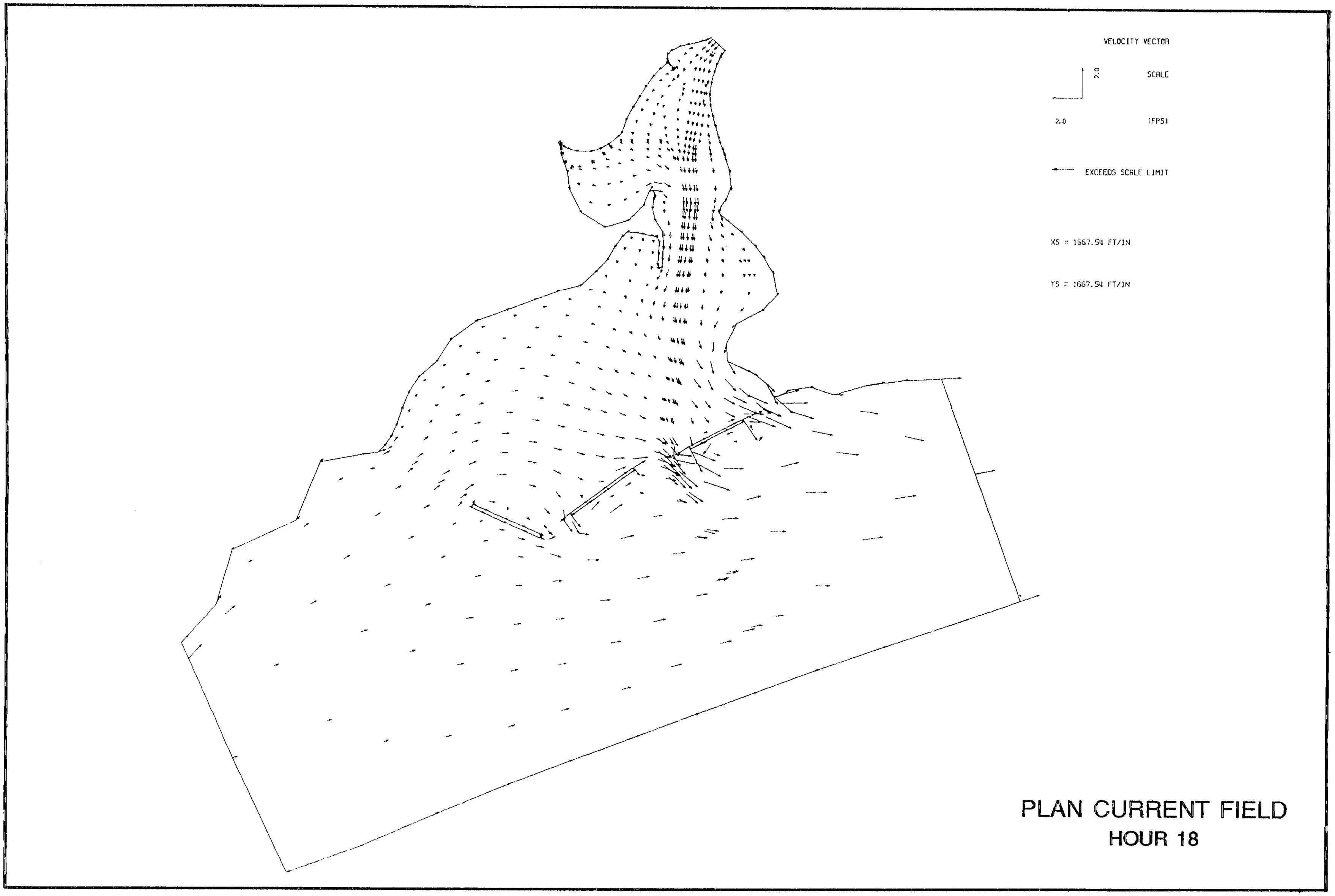
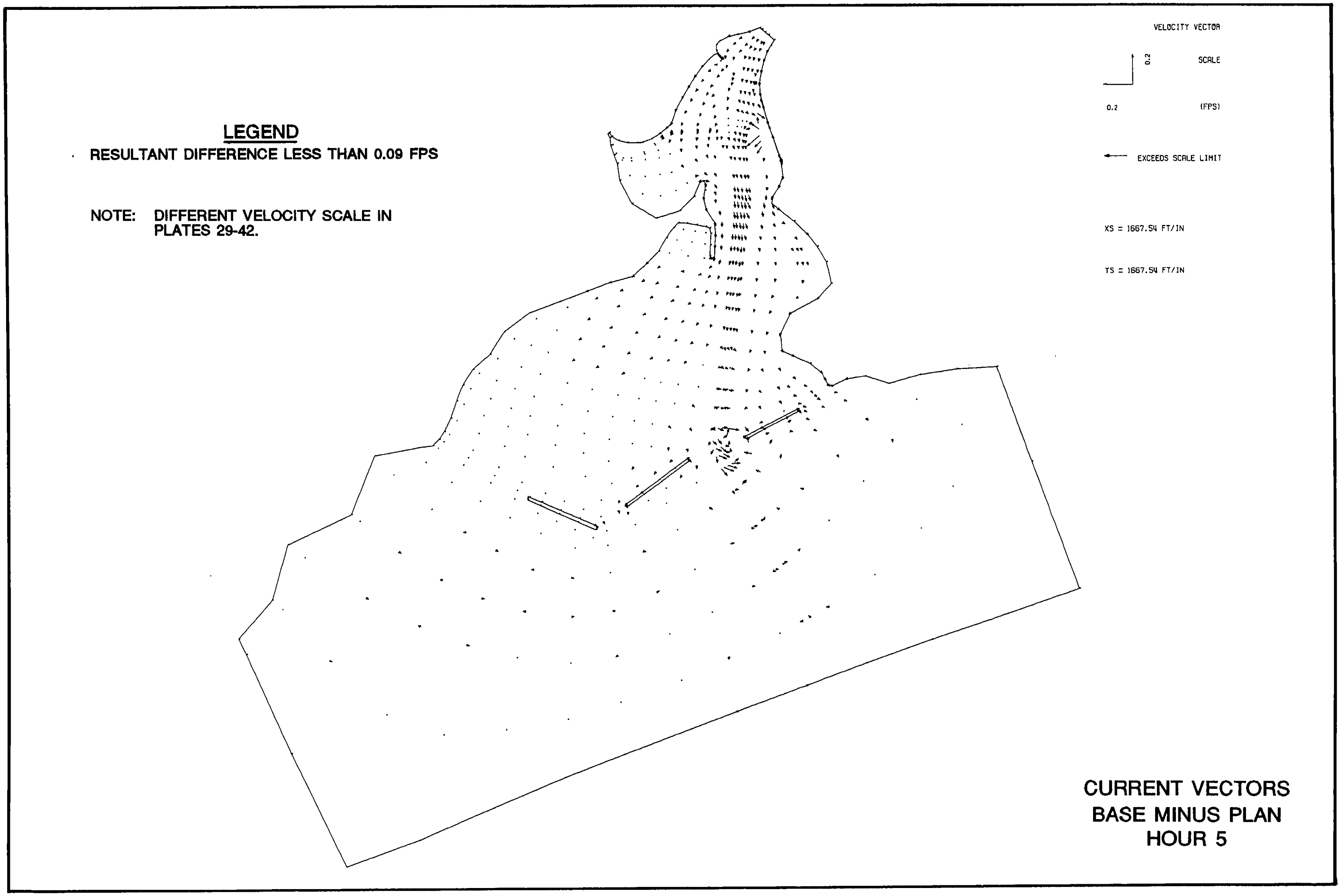


PLAN CURRENT FIELD
HOUR 17

PLATE 28

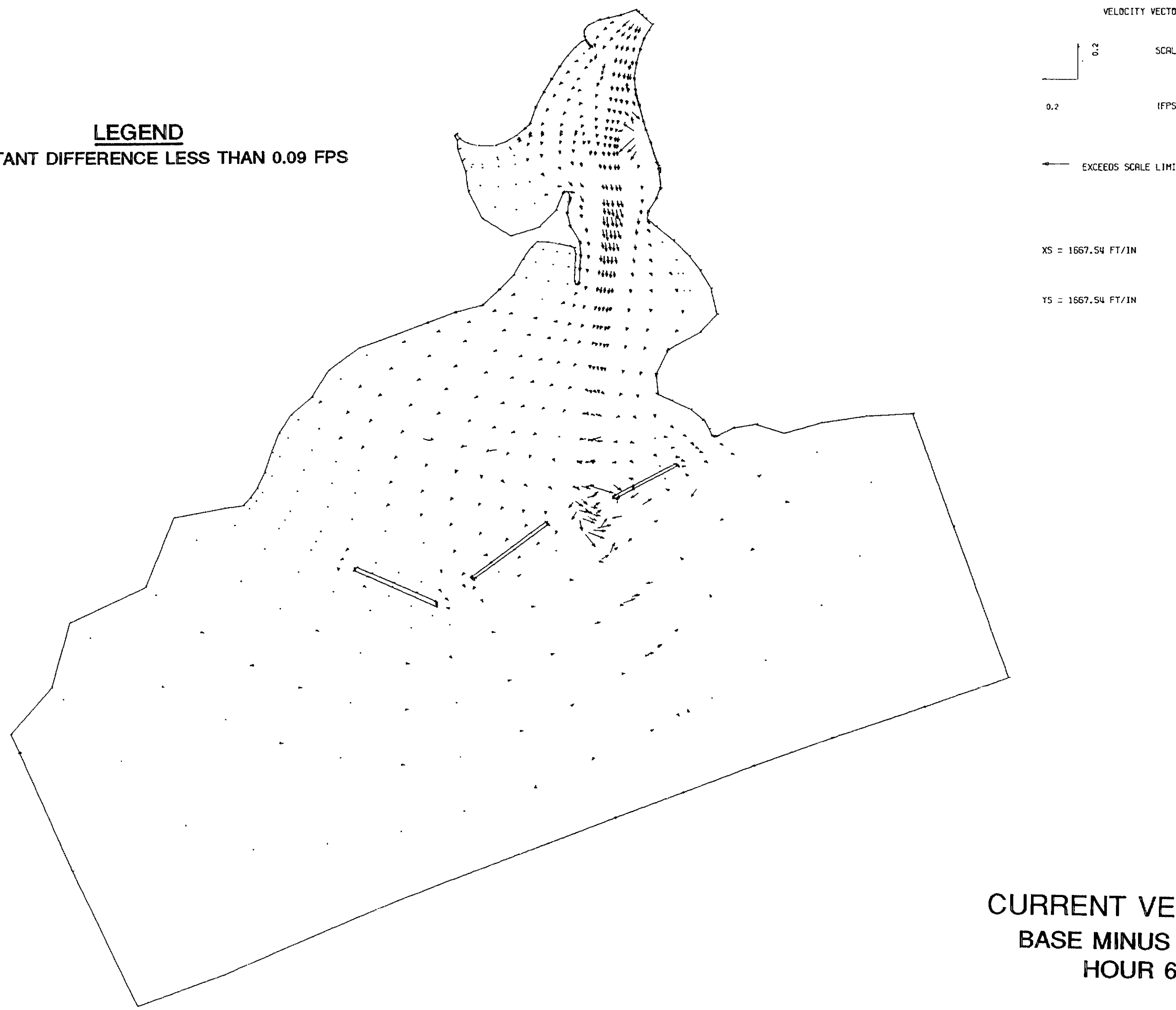


PLAN CURRENT FIELD
HOUR 18



CURRENT VECTORS
BASE MINUS PLAN
HOUR 5

PLATE 30



LEGEND

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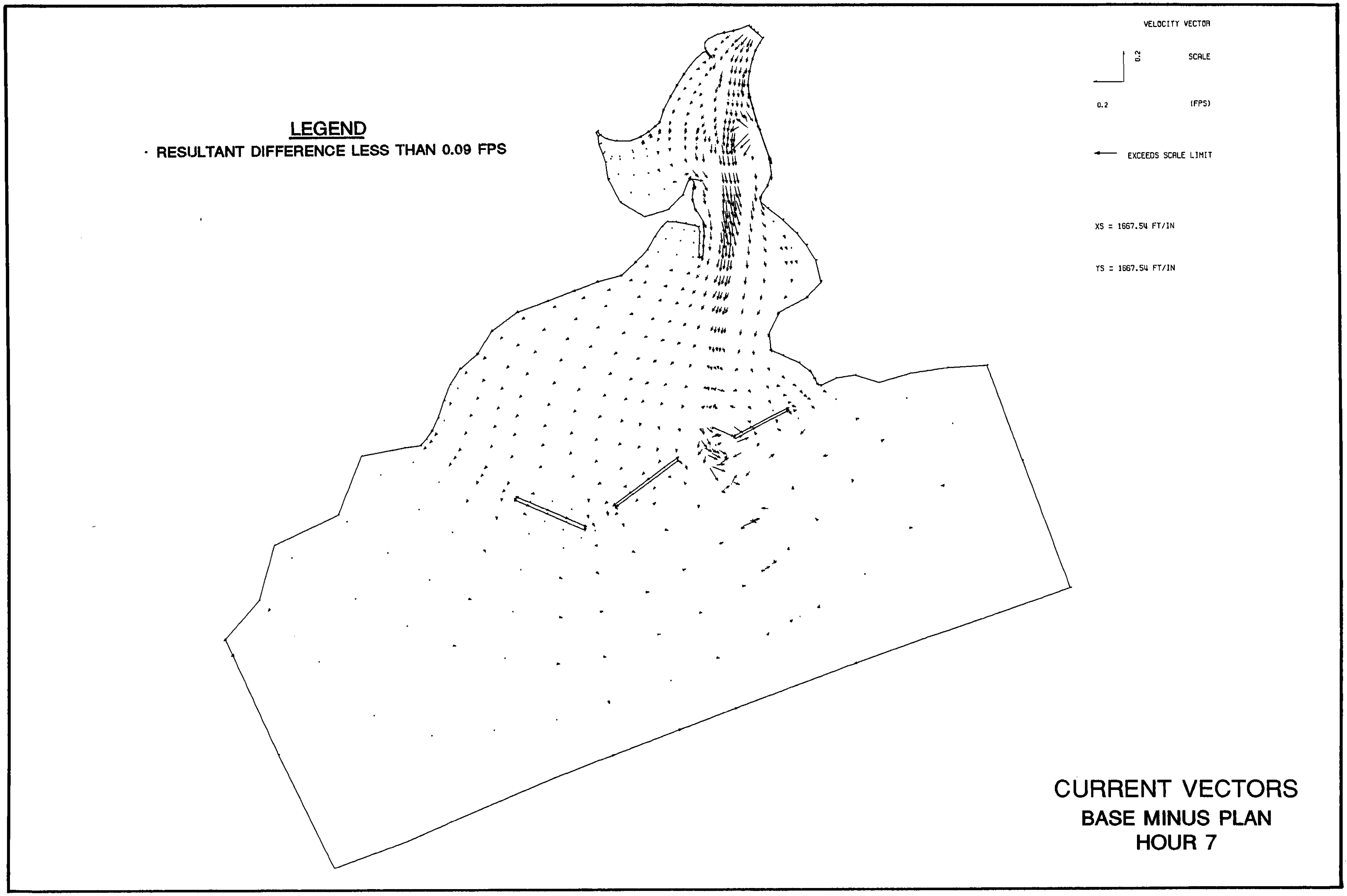
CURRENT VECTORS
BASE MINUS PLAN
HOUR 6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0.2
(FPS)
EXCEEDS SCALE LIMIT
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CURRENT VECTORS
BASE MINUS PLAN
HOUR 7

PLATE 31

LEGEND

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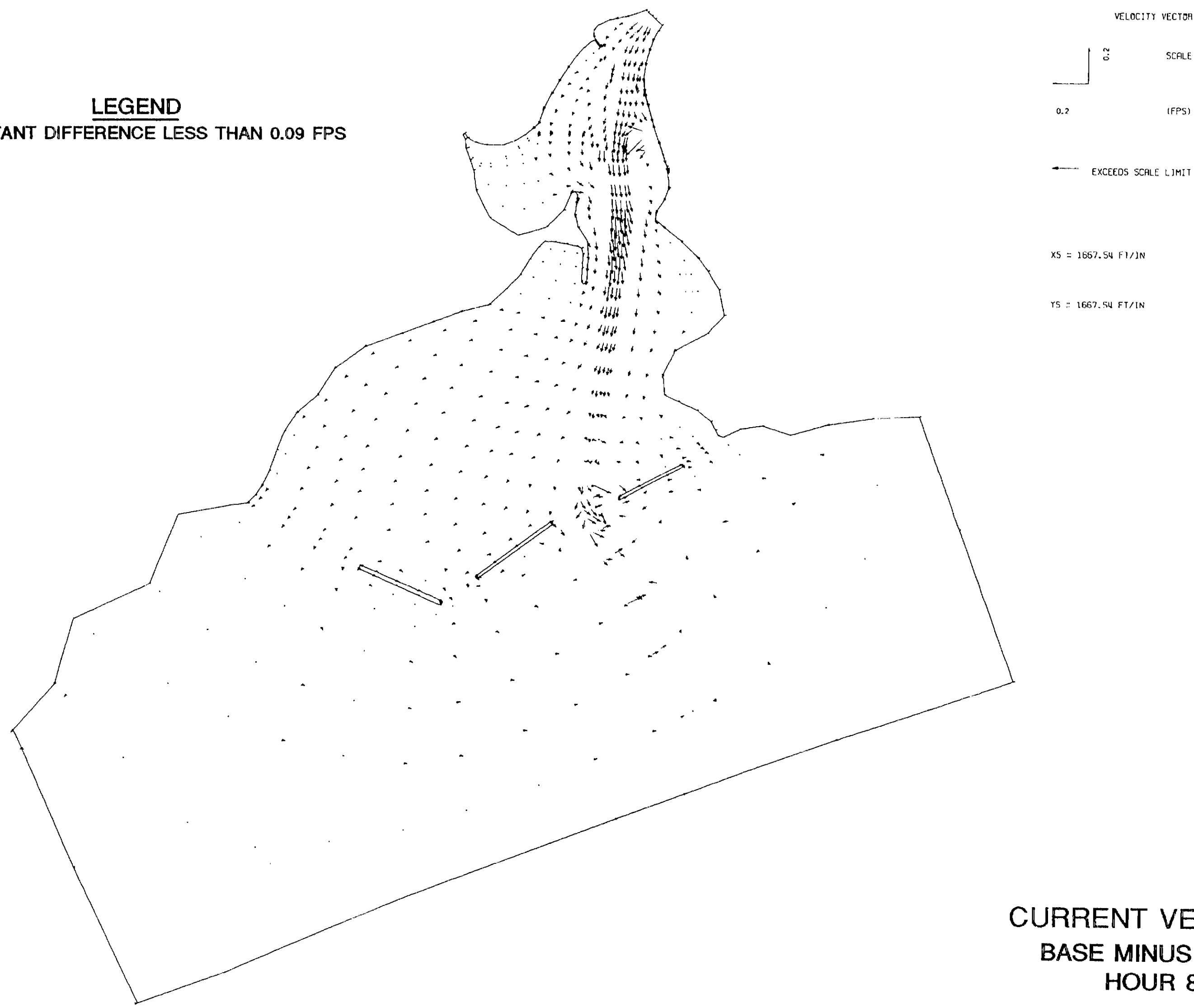

CURRENT VECTORS
BASE MINUS PLAN
HOUR 8

LEGEND

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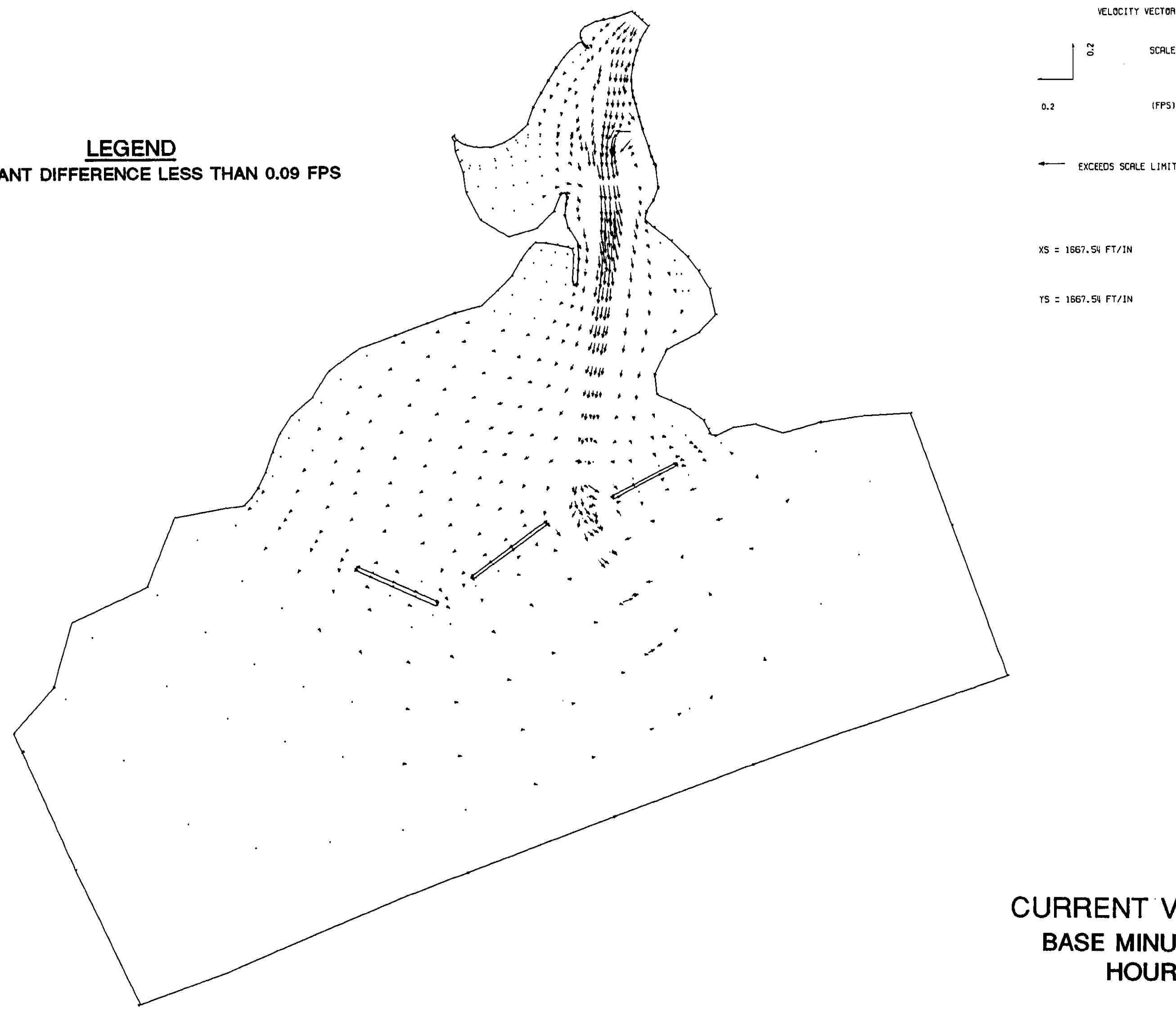

CURRENT VECTORS
BASE MINUS PLAN
HOUR 9

PLATE 34

LEGEND

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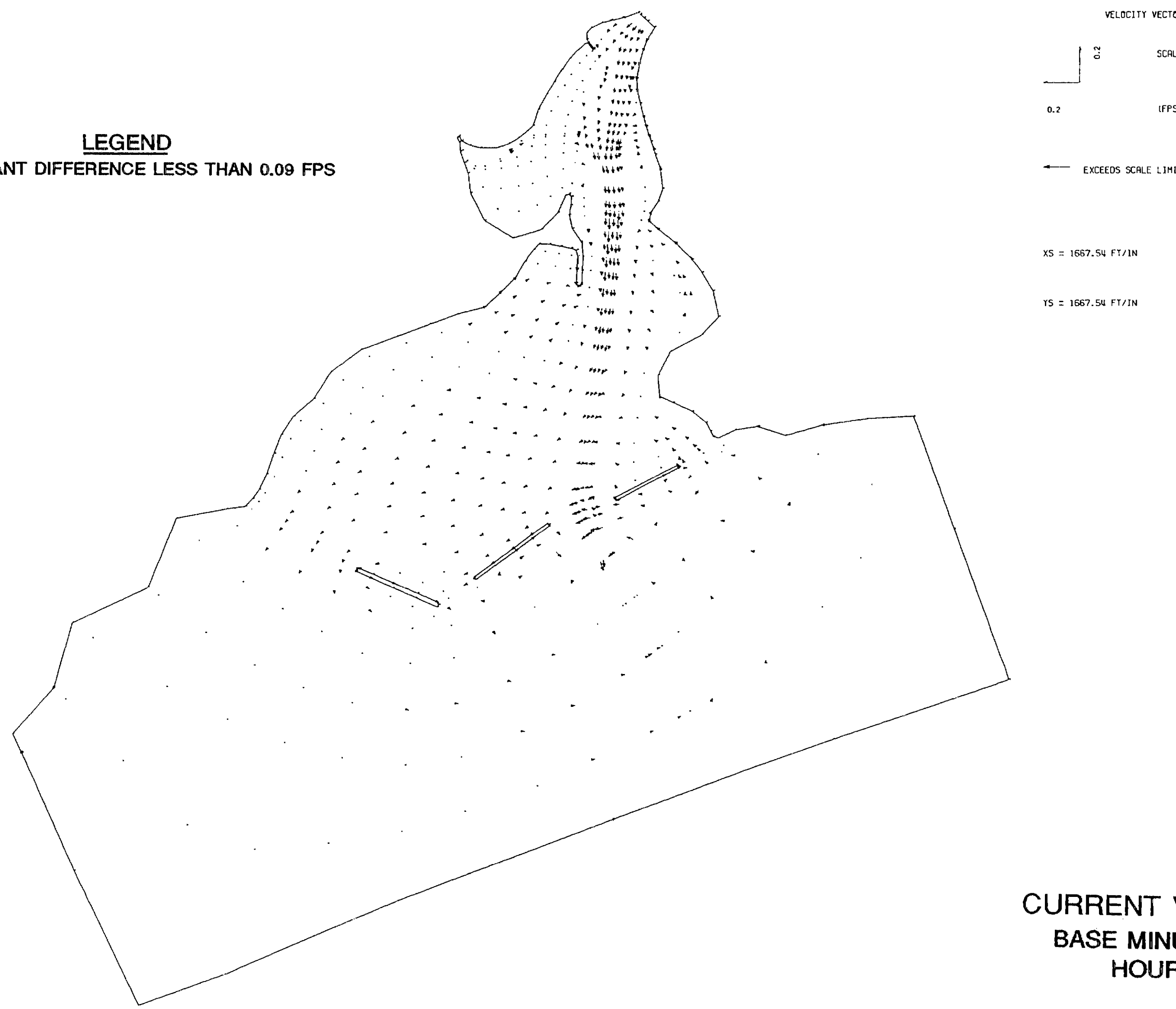
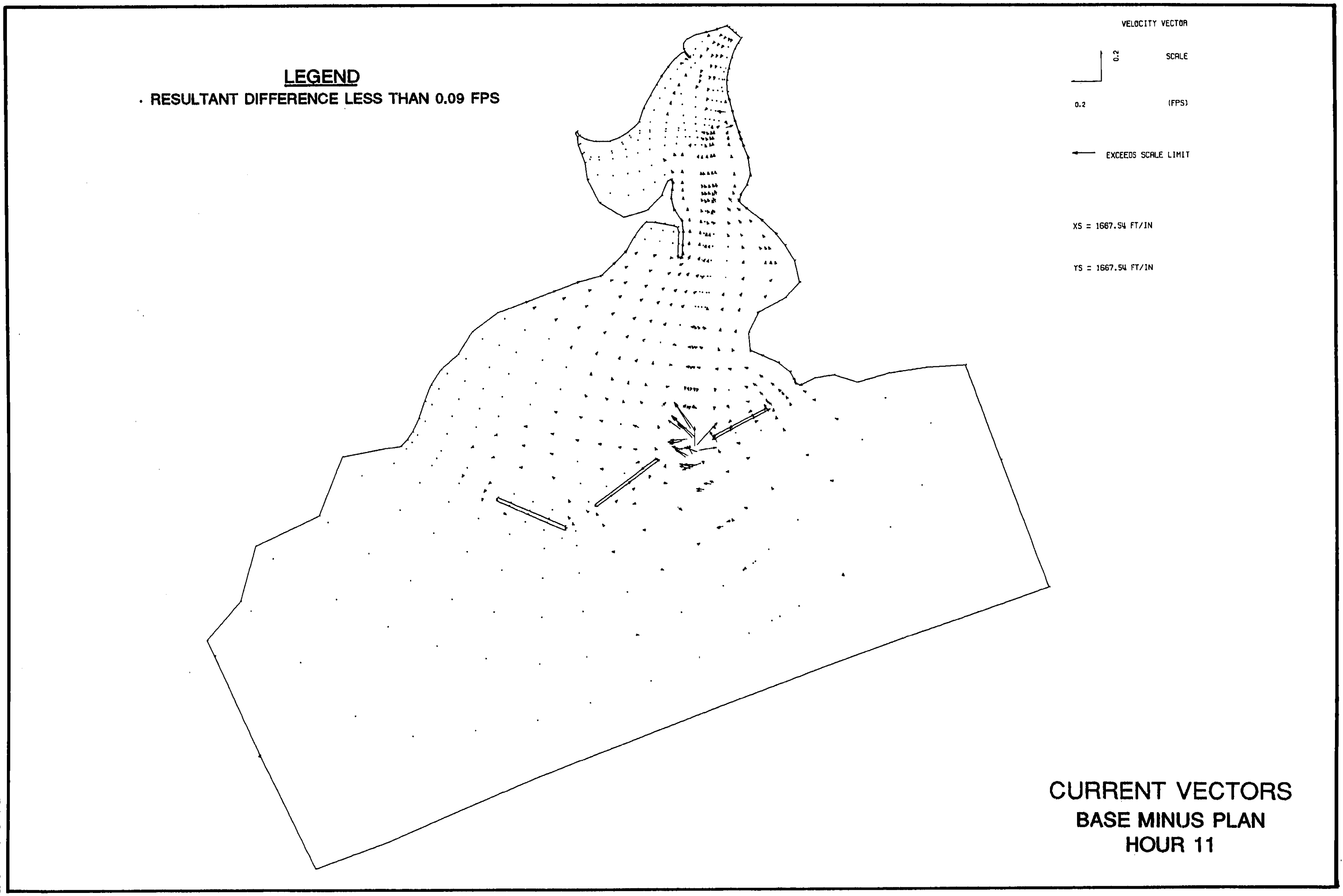


CURRENT VECTORS
BASE MINUS PLAN
HOUR 10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SCALE
0.2
(FPS)
EXCEEDS SCALE LIMIT
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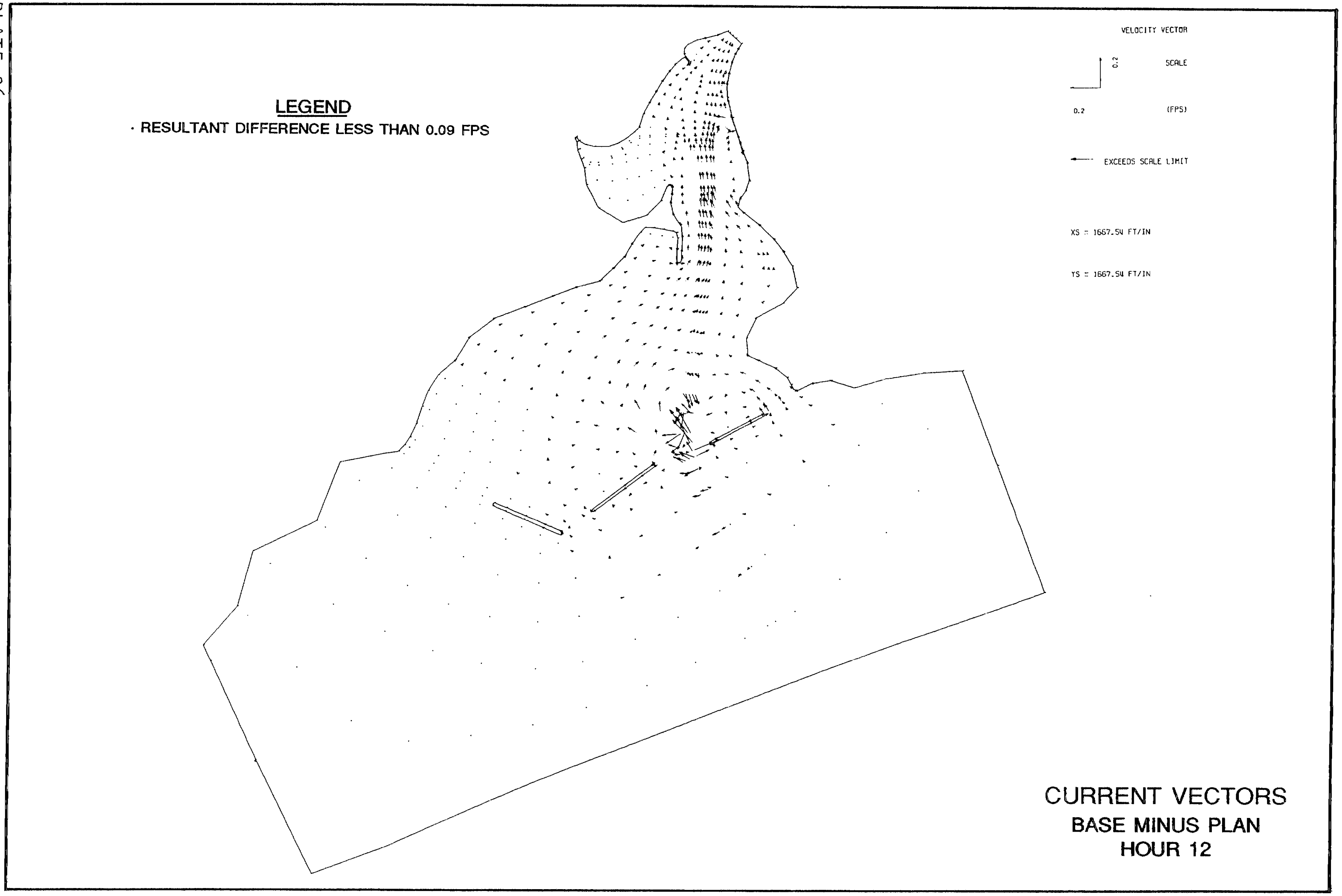
YS = 1667.54 FT/IN
CURRENT VECTORS
BASE MINUS PLAN
HOUR 11

PLATE 35


LEGEND
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VELOCITY VECTOR
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SCALE
0.2
(FPS)
EXCEEDS SCALE LIMIT
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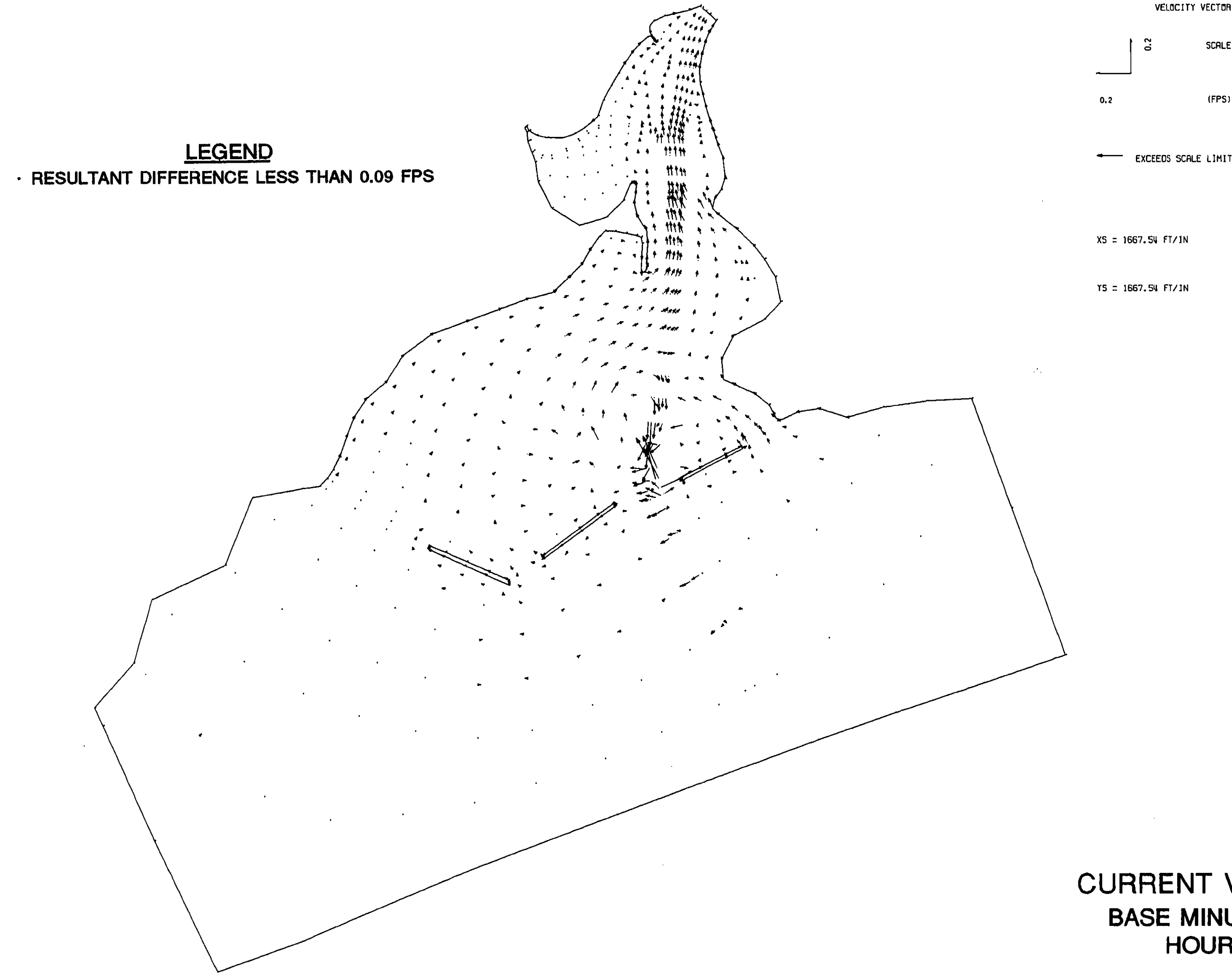
YS = 1667.54 FT/IN
CURRENT VECTORS
BASE MINUS PLAN
HOUR 12



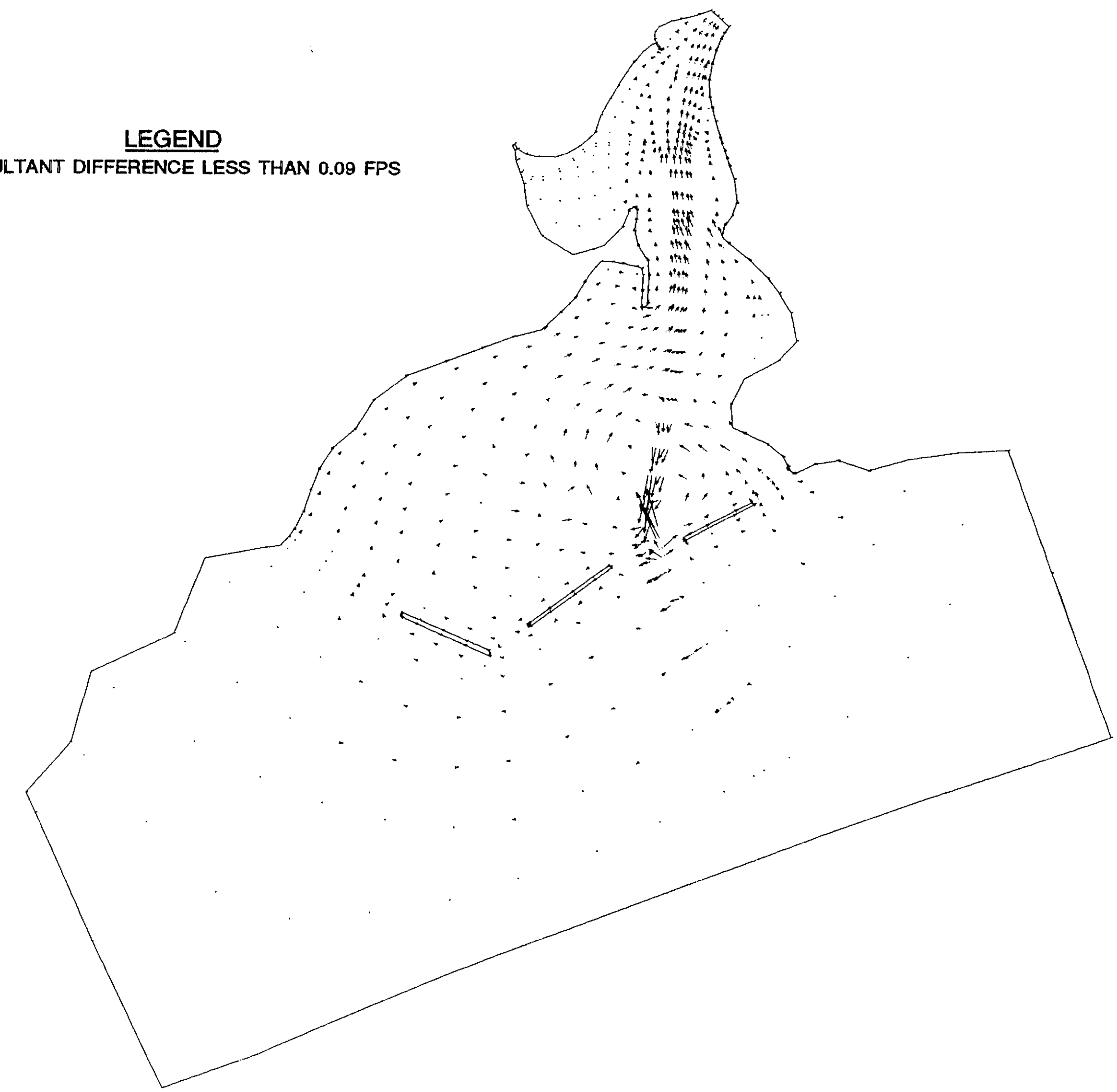
CURRENT VECTORS
BASE MINUS PLAN
HOUR 13

PLATE 37

PLATE 38

LEGEND

· RESULTANT DIFFERENCE LESS THAN 0.09 FPS



VELOCITY VECTOR

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0.2 (FPS)

EXCEEDS SCALE LIMIT

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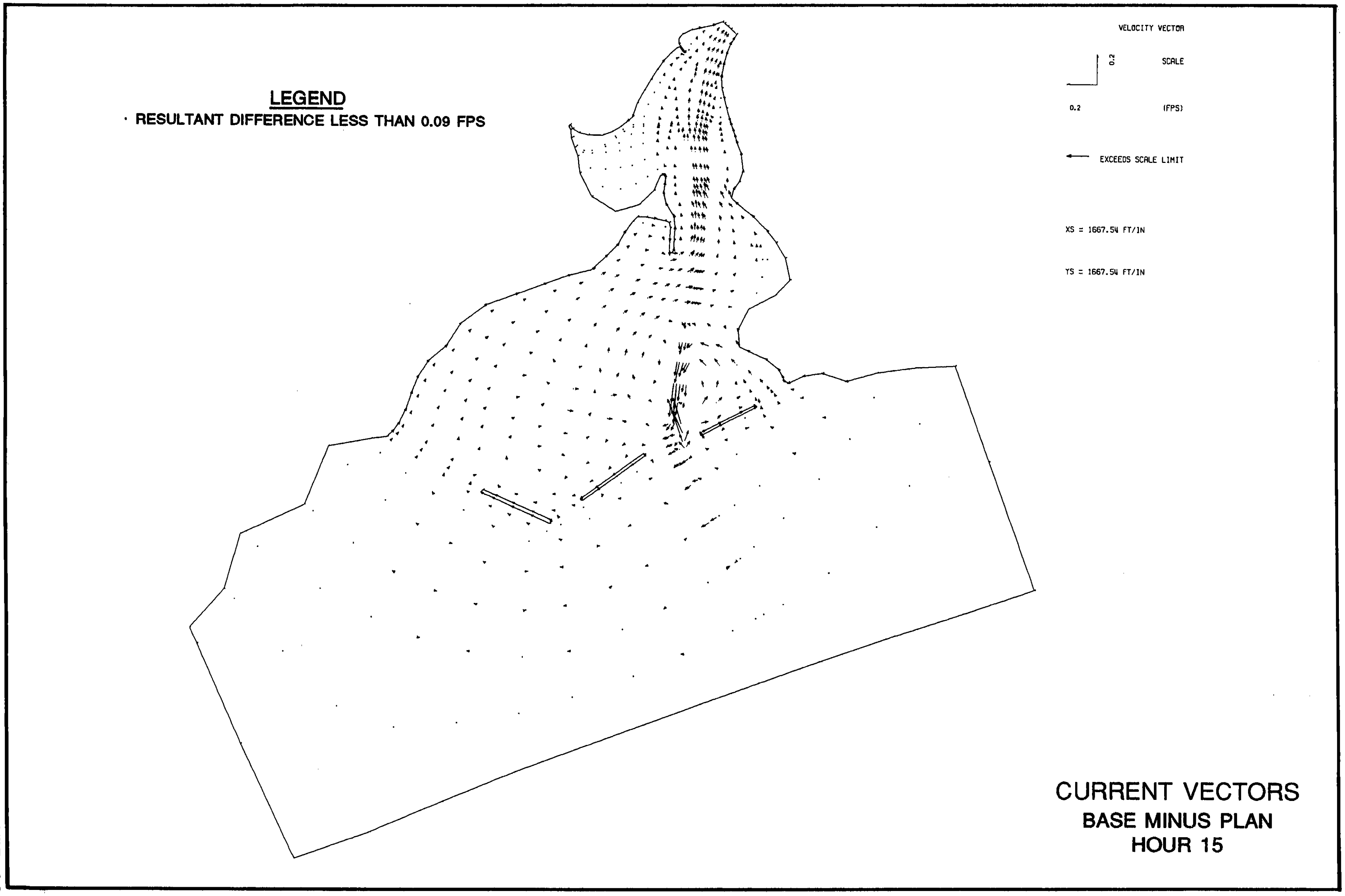
YS = 1667.54 FT/IN

CURRENT VECTORS

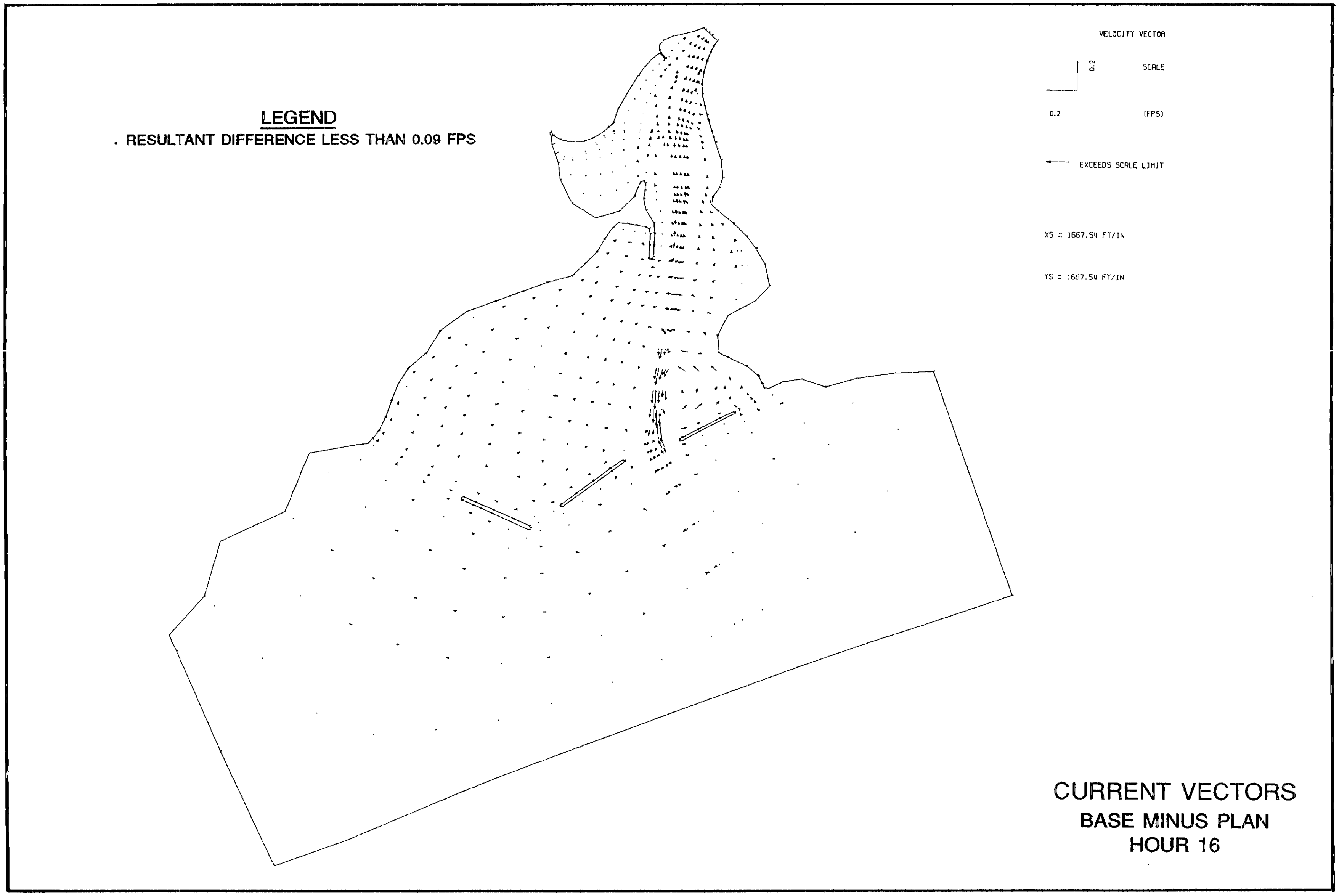
BASE MINUS PLAN

HOUR 14

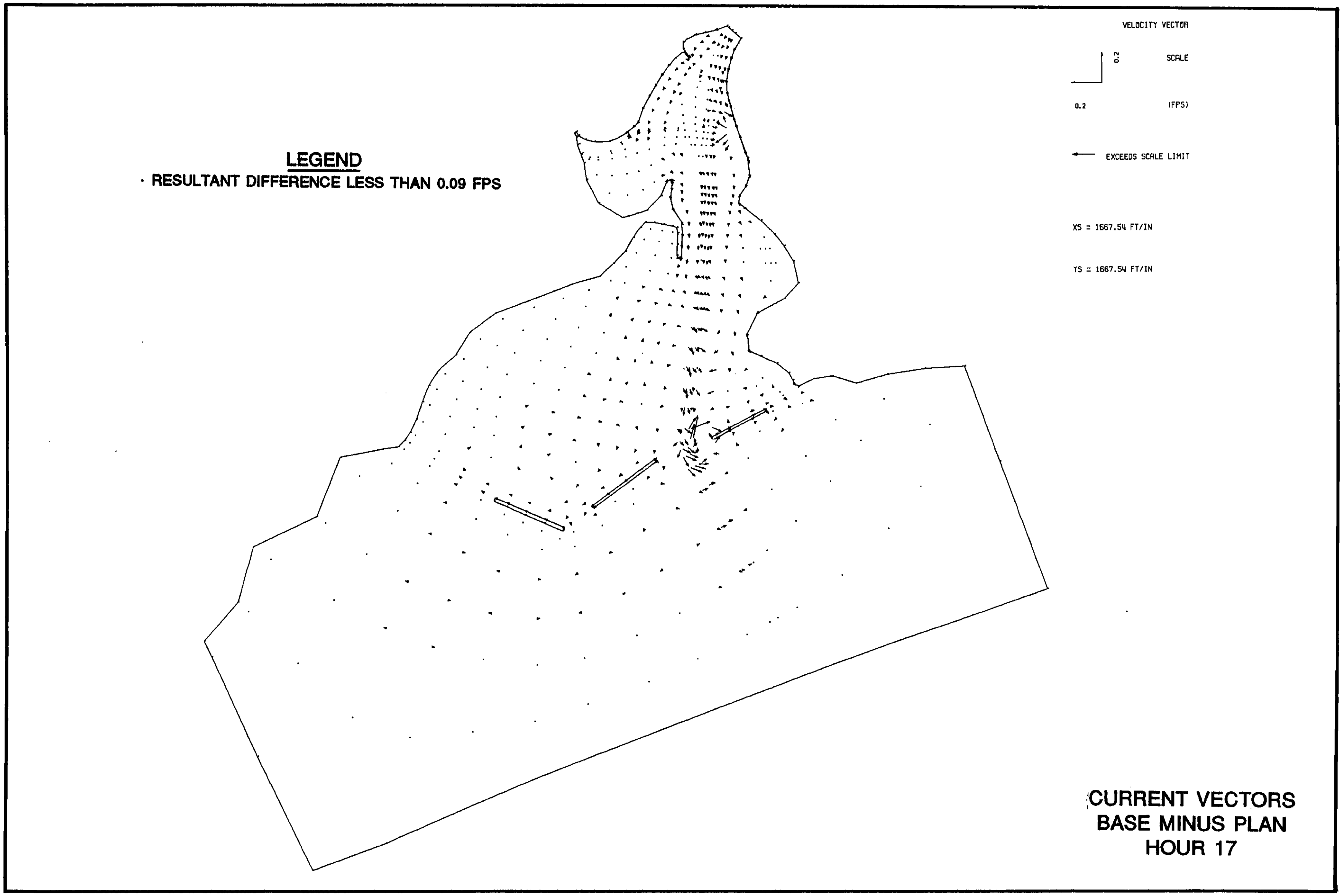


CURRENT VECTORS
BASE MINUS PLAN
HOUR 15

PLATE 39



CURRENT VECTORS
BASE MINUS PLAN
HOUR 16


LEGEND
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VELOCITY VECTOR
0.2
SCALE
0.2
(FPS)
EXCEEDS SCALE LIMIT
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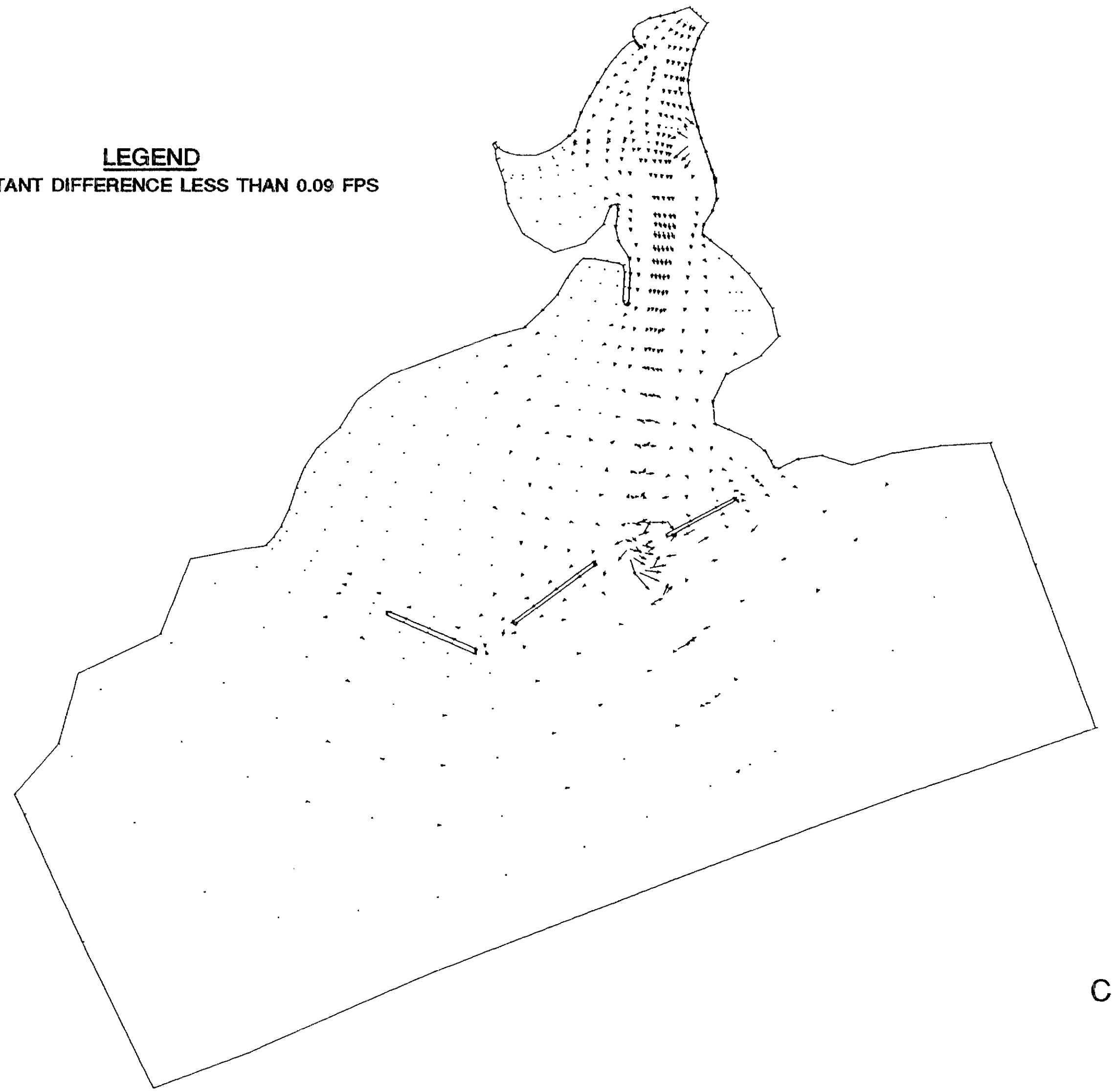
YS = 1667.54 FT/IN
CURRENT VECTORS
BASE MINUS PLAN
HOUR 17

PLATE 41

PLATE 42

LEGEND

· RESULTANT DIFFERENCE LESS THAN 0.09 FPS



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0.2 (FPS)

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CURRENT VECTORS

BASE MINUS PLAN

HOUR 18